The effect of visibility in the integration of lean and agile for supply chains

By

Xin Wang

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Declaration

I, Xin Wang, hereby declare that the work presented in this thesis is my original research. Other sources of information used in this research have been acknowledged. The efforts of the participants in the research have been indicated clearly.

This work has never been submitted for an academic degree at other university.

Abstract

Over the last two decades, supply chain researchers have sought to find appropriate ways of achieving lean and agile “LeAgile” supply chains. However, the differences in the priorities of the lean and agile paradigms multiply the challenges in lean and agile combinations. The most discussed approaches in the literature are the decoupling point and the late customisation (postponement) strategies. Supply chain visibility as a solution is less frequently discussed though the ‘Smarter Supply Chain of the Future’ report states that ‘*70% of supply chain leaders view Supply Chain Visibility as their number one challenge... the need to ‘see’ and act on the right information*’ (IBM, 2010). Technologies such as EDI and RFID have been implemented to improve visibility, have not gained general acceptance. Newer, low cost ‘Cloud’ solutions may be able to address the need better.

Previous research has suggested that increasing information visibility improves supply chain performance, though the relationship between the degree of visibility and resulting performance does not appear to have been addressed. Therefore, a role playing simulation methodology was devised to evaluate the effect of supply chain visibility on improved LeAgile supply chain performance. Role playing simulations better emulate the human control actions in supply chains, but can also suffer/benefit from traits such as learning.

A low cost Web and Cloud based system was devised to enable visibility and communication in the simulation. Different information sharing configurations (visibility levels) were evaluated for a typical four-echelon supply chain. The results show a correlation in improved supply chain LeAgility with the degree of visibility of demand and/or operational information, but this was not a linear relationship. A degree of ‘digital’ waste eroded performance with increasing levels of visibility.

Comparison simulations were then conducted to compare the supply chain visibility strategy with ‘decoupling point’ and ‘postponement’ strategies for the same four-echelon supply chain. The results suggest that after adopting the supply chain visibility approach, the overall performance of the simulation supply chain increased by 26.3% and 26.4% compared to the decoupling point and postponement approach scenarios. Further simulation experiments with different supply chain configurations are required to test the wider applicability of the results.

List of Abbreviations

BI	Business Intelligence
CF	Centralised Forecast
CPFR	Collaborative Planning, Forecasting and Replenishment
DC	Distribution Centre
DCF	Direct Customers' Forecast
DMN	Dynamic Manufacturing Network
DP	Decoupling Point
EDI	Electronic Data Interchange
EIS	Executive Information System
ERP	Enterprise Resource Planning
EU	Europe
FAT	Final Assembly and Test
FDDM	Forecasted Demand Distributing Method
FDI	Foreign Direct Investment
FG	Finished Goods
FGI	Finished Goods Inventory
HA	Humanitarian Aid
HP	Hewlett-Packard
ICT	Information and Communications Technology
IMAGINE	Innovation end-to-end Management of Dynamic Manufacturing Networks

IT	Information Technology
KPI	Key Performance Indicator
MES	Manufacturing Execution Systems
MIT	Massachusetts Institute of Technology
MRP	Materials Requirement Planning
MSc	Master of Science
PDTM	Planned Demand Transferring Method
RD	Real Demand
RFID	Radio Frequency Identification
RM	Raw Material
SCOR	Supply Chain Operations Reference
SCV	Supply Chain Visibility
SME	Small and Medium Enterprises
SOA	Service Oriented Architecture
US	United States
VMI	Vendor-Managed Inventory
WMCCM	West Midlands Collaborative Commerce Marketplace
WS	Web Services

Accompanying Materials

- 1 CD including electronic copy (.PDF) and appendices

1

Introduction

1.1 Research motivation

In the course of global economic fluctuation, companies are facing an increasingly complex business environment. The increased complexity in supply chains has caused longer lead times and lead-time variability, more pipeline inventory, and the increasing need of logistics control (Heaney, 2011). This has significantly increased supply chain management costs in the current highly uncertain environment. Increasingly demanding customer requirements exacerbate this situation. Customers are looking for complete solutions at lower prices, but with higher quality and faster lead times, and they have the internet and IT systems to help them find alternative suppliers if necessary. Companies increasingly need to be 'LeAgile' in order to reduce costs whilst responding swiftly to the rapid changes in both demand and supply.

Scholars have sought to find appropriate ways of achieving a LeAgile supply chain. Christopher and Towill (2000) summarised four practical approaches for creating a LeAgile supply chain: the Pareto curve approach, separation of 'Base' and 'Surge' demands approach, the decoupling point approach and the late customisation (postponement) approach. And the decoupling point approach and the late customisation approach are the most discussed approaches in literature.

The decoupling point approach can be defined as the boundary between lean operation and agile operation in a supply chain, where lean principles can be adopted upstream from the boundary and agility is applied downstream from the boundary. Many researchers have investigated the decoupling point in order to identify its appropriate position in supply chain networks (Mason-Jones and Towill, 1999; Olhager *et al.*, 2006; Stevenson and Spring, 2007; Rahimnia and Moghadasian, 2010). For example, the material decoupling point should be placed as close to the market as possible (Mason-Jones and Towill, 1999), and the information decoupling point should be held as far upstream as possible in the supply chain, in order to enable as many members as possible to access demand data (Stevenson and Spring, 2007). The positioning of the decoupling point can be viewed as identifying a balance between competitive advantages, and cost and complexity. There are many factors which could influence the positioning of the decoupling point in a supply chain network. Such factors include the market, production lead time, demand variance and delivery time (Olhager, 2003).

Results of many researchers, such as Olhager *et al.* (2006), Fan *et al.* (2007), and Sun *et al.* (2008) have suggested that the decoupling point approach is capable of satisfying customer needs in the current volatile business environment, in both conceptual and real supply chains. Rahimnia and Moghadasian (2010) extended the decoupling point strategy to professional services, such as hospitals, and showed that more patients were given care due to the reduced lead times and costs, after the decoupling points in healthcare supply chains were identified. However, one common issue revealed by their research is the great difficulty of deriving the correct and suitable strategic inventory at the decoupling points to balance the operational stability and the market requirement in both theory and practice.

The late customisation (postponement) strategy, which is related to the decoupling point strategy, is recognised as an effective agile strategy which has been widely adopted (*e.g.* Dell). Having a postponed configuration allows a "mass customisation" strategy, and presents numerous advantages. Christopher and Towill (2000) summarised the benefits of implementing a postponement strategy as lower inventory, improved flexibility and higher forecasting accuracy. Chen and Lee (2009) suggested that sharing information together with an order postponement strategy reduces the bullwhip effect. Additionally, Graman and Sanders (2009) showed that a late customisation strategy is more appropriate than accurate forecasting in achieving agility in terms of inventory reduction whilst maintaining a level of customer service; however, their results also shown significant costs of increasing capacity at the postponement stage. Therefore, it is suggested that a LeAgile supply chain is only achieved through late customisation strategy when the supply chain focuses on the lean principle to eliminate waste (Fan *et al.*, 2007; Graman and Sanders, 2009; Sehgal, 2010).

Previous research has demonstrated the impact of these approaches for achieving supply chain LeAgility (Olhager, 2006; Sun et al, 2008; Chen and Lee, 2009; Graman and Sanders, 2009; Rahimnia and Moghadasian, 2010). However, it has not examined how to design those approaches in practice, since the application may vary from situation to situation according to the extent to which leanness or agility is desired. This research discusses disadvantages of the LeAgility approaches in literature in the context of the current business environment, and suggests that their limitations have obstructed their business applications. In life, enhanced visibility of the situation may enable a more agile response to danger, and increasingly technology is deployed to provide increased visibility. For example the internet can tell us where we can find a product cheaper, or quicker or more locally. In this research the author explores supply chain visibility enabled by the internet as an approach to addressing the needs for LeAgility.

LeAgility through supply chain visibility is achieved by creating an information driven supply chain. Supply chain partners in this virtual supply chain can access shared demand and operational information, and make their operational decisions after 'seeing' what is happening. An analogy to explain supply chain visibility: Imagine you are in a room full of objects, and that your mission is to find a path to the exit as quickly as possible. However, the room is dark because the light is turned off. Logically, the first move in this situation is to turn the light on and then find a possible way to clear a path to the exit, once you are able to see everything. This is the so-called supply chain visibility.

The definition of supply chain visibility is ill-defined and in the literature, however majority of the research defines supply chain visibility from the perspective of information sharing (Barratt and Oke, 2007; Francis, 2008; Holcomb et al, 2010; Goh et al, 2009). Achieving visibility requires sharing information related to all aspects of supply chain activities with supply chain partners (Holcomb *et al.*, 2010). Supply chain members are able to 'see' and act according to the current status of the supply chain through sharing critical information in real time. This research defines supply chain visibility an IT perspective, and explores an supply chain visibility solution which captures the key characteristics of visibility to tackle the core issues of uncertainty and improving LeAgility in a supply chain (Chapter 2.3.1)

1.2 Research gap

This research reviews the four approaches (the Pareto curve approach, separation of 'base' and 'demand' approach, the decoupling point approach and the late customisation approach) in literature for creating LeAgile supply chains (Chapter 2.2). However, the method with which to implement those methods was not clearly defined, since they may vary from situation to situation according to the extent to which leanness or agility is desired. The author discusses their disadvantages in the context of the current business environment and addresses the gap by exploring supply chain visibility as an approach.

Previous research has suggested that increasing information visibility improves supply chain performance by using different methodologies. Simulation and modelling are the most used methods in the literature to measure visibility and its impact on supply chain performance (Chen et al, 2000; Lee et al 2000; Yu et al,2001; Gavirneni, 2002; Croson and Donohue, 2003; Disney and towill,2003; Ryu et al,2009; Sahin and Robinson, 2005). The results of these authors demonstrated the contributions to qualify the effect of increased visibility on improving supply chain performance; Other researchers focused on empirical studies, most of them are relied on surveys and case studies (Frohlich and Westbrook, 2002; Zhao et al., 2002; Kim et al., 2006; Kim, 2009; Zhou and Benton, 2007; Wong and Boon-itt, 2008; Kaipia and Hartiala, 2006; Barratt and

Oke, 2007; Bartlett et al., 2007; Bailey and Francis, 2008; Holcomb et al, 2010). For example, Barratt and Oke (2007) suggested that achieving high level of visibility on demand, process and inventory levels could bring competitive advantage to supply chains by analysed five case studies; Holcomb *et al.* (2010) identified the competitive advantage granted by improving visibility as reduced operation costs and increased customer service level by analysed the 278 surveys from North American and European firms. However, most authors focused mainly on simplified supply chains (i.e. two-tier supply chain) and failed to provide a quantification of the benefits of increased visibility in complex supply chains or networks. In fact, real supply chains are more complex and a comprehensive measure of the effect of visibility to complex supply chains or networks is lacking (Caridi et al, 2010).

More importantly, the majority research attempted to explore the relation between the increased visibility and improved supply chain performance in many dimensions based on the definitions of visibility (e.g. information sharing, information accuracy, quality of exchange information, timeliness) (Simatupang and Sridharan, 2005; Kaipia and Hartiala, 2006; Barratt and Oke, 2007; Zhou and Benton, 2007; Caridi et al, 2010). There are two key elements of achieving supply chain visibility: shared information content and information sharing frequency. The majority of the research focused on the impact of the shared information on the supply chain performance. However, the information sharing frequency and its impact on supply chain performance, especially supply chain LeAgilty, has been little explored. Thus the focus of this research is to explore the relation between the differing levels of supply chain visibility and the resulting improvement supply chain LeAgility for a complex supply chain (a four-tier supply chain).

1.3 Research question and objectives

Logic suggests that improved visibility will lead to “better” supply chain performance. Is this “better” performance LeAgile in nature? The following research question was phrased to address this:

To what extent can a LeAgile supply chain be achieved through improved supply chain visibility?

This question can be broken down into a number of resulting subquestions that have been addressed in this research. These are:

1. To what extend can the supply chain LeAgility be improved after sharing the customer demand related information?
2. To what extend can the supply chain LeAgility be improved after sharing the operational related information?
3. What are the advantages of supply chain visibility approach for creating a LeAgility supply chain versus the decoupling point and postponement approaches?

1.4 Thesis structure

The research gap was identified in chapter two by reviewing the four approaches in the literature for creating LeAgile supply chains. Supply chain visibility was then proposed as a solution to address this gap. A role playing simulation methodology was adopted to evaluate the effect of supply chain visibility on improved LeAgile supply chain performance (chapter three). The detailed simulation design and different information sharing configurations (visibility levels) for a typical supply chain were presented in chapter four. The results from the simulations were analysed in chapter five in order to access the extent of supply chain LeAgility with increased visibility, and explore the advantages of visibility over the decoupling point and postponement approaches. Chapter six discussed the correlation between visibility and supply chain LeAgility, and evaluated its business implications. The conclusion and future work were summarised in chapter seven. The thesis structure is illustrated in Figure 1.1:

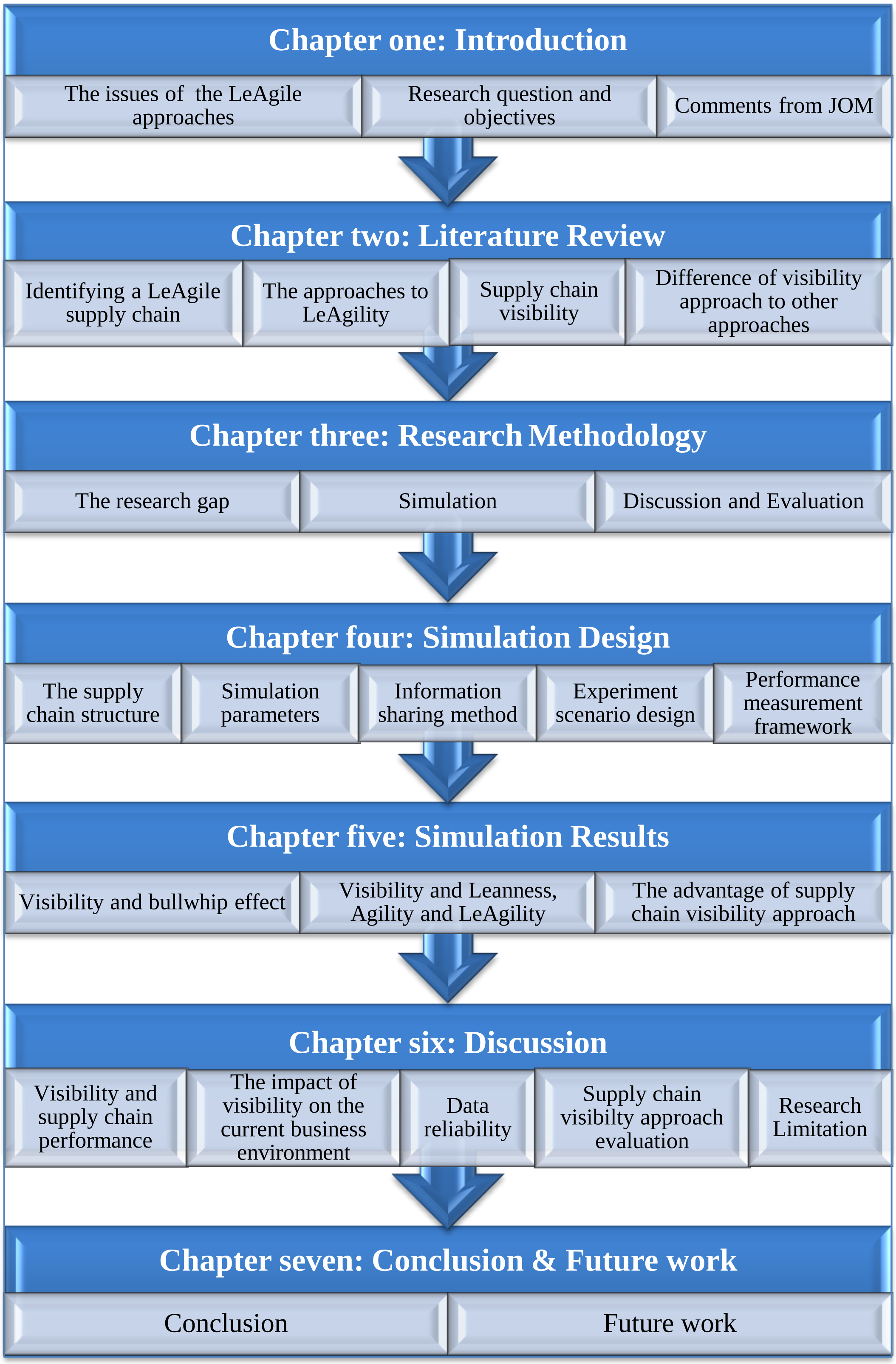


Figure 1.1: Thesis structure

2

Literature Review

The four approaches, known as the Pareto curve approach, separation of 'Base' and 'Surge' demands approach, the decoupling point approach, and the late customisation (or postponement) approach, suggested in the literature for creating LeAgile supply chain were reviewed. However, they are no longer effective in the current highly uncertain business environment. Supply chain visibility was proposed as an attempt to address this gap. The definition of supply chain visibility and its issues were then discussed to establish its values. The information sharing structures and current technologies for enabling visibility were also reviewed.

2.1 Identifying a LeAgile supply chain

The concept of LeAgile has been developed, in both manufacturing and services contexts, by many researchers (Vorst *et al.*, 2001; Aitken *et al.*, 2005; Mistry, 2005; Sanderson and Cox, 2008; Rahimnia and Moghadasian, 2010). A LeAgile supply chain is generally agreed by many researchers to be an agile supply chain which adopts many lean principles in supply chain management (Narasimhan *et al.*, 2006; Scholten *et al.*, 2010). A LeAgile supply chain should have both lean and agile characteristics. It attempts to combine low cost from lean principles with the flexibility provided by agile ones.

According to Agarwal *et al.* (2006), LeAgility is the improvement in supply chain performance related to the ability of supply chains to quickly respond to volatile market changes whilst keeping costs low. It focuses on solving the problem of how to quickly respond to customer needs with the lowest cost in an unpredictable market.

Out of the lean, agile and LeAgile strategies, there is not one that is better or worse than the others. They each address different market opportunities based on their individual characteristics. The following sections review their characteristics and identify the situations in which they may be used.

2.1.1 Demand uncertainty and product variety

The lean paradigm is generally considered as the ideal solution for supply chains which have the predictable demand with low product variety, such as Coca Cola (Naylor *et al.*, 1999; Christopher and Towill, 2000; Mason-Jones *et al.*, 2000a; Mason-Jones *et al.*, 2000b). On the opposite, the agile paradigm is considered the best to be used for a less predictable demand with high product variety, such as fashion clothes (Naylor *et al.*, 1999). Figure 2.1 shows the lean, agile and LeAgile strategies in the matrix of demand uncertainty vs. product variety. The vertical axis shows the production variety from low to high; the horizontal axis shows the demand uncertainty. Figure 2.1 illustrates that a LeAgile supply chain has the advantage of dealing with a volatile customer demand with a medium level of product variety. The LeAgile strategy balances the lean and agile paradigm to meet unpredictable demands whilst reducing cost (Bruce *et al.*, 2004).

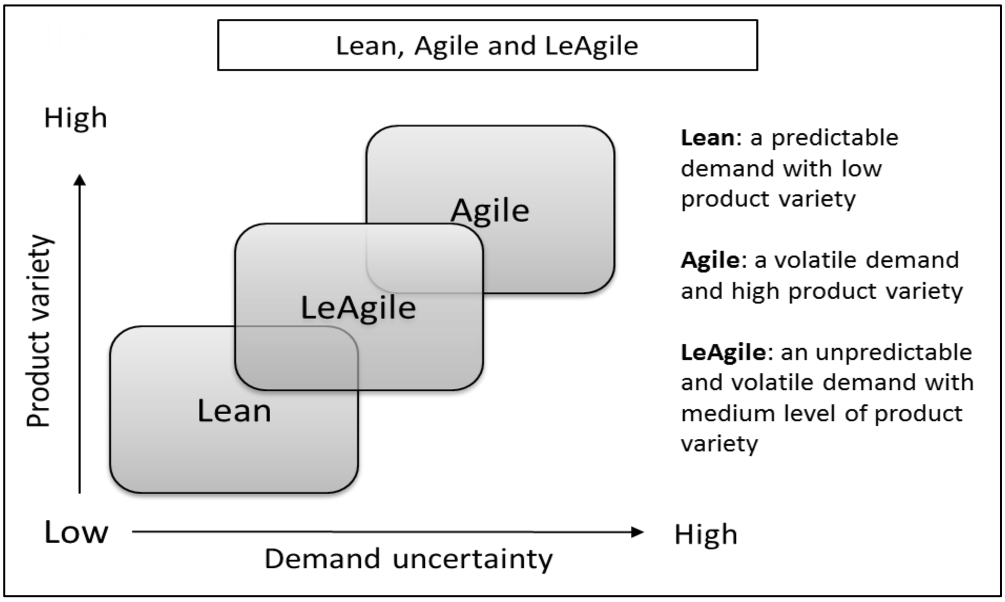


Figure 2.1: Lean, Agile or LeAgile

2.1.2 Market qualifiers and market winners

Lean and agile supply chains have also been compared from the point of view of market qualifiers and market winners (Mason-Jones *et al.*, 2000a). They were found to share the mutual qualifiers of quality and lead time. However, the lean supply chain focused on reducing the cost, whilst the agile supply chain pursued customer service satisfaction (availability) as the market winner. In the case of LeAgile supply chains, they win the market by focusing to obtain both paradigms in a balanced relationship within one supply chain (Christopher and Towill, 2001). Table 2.1 illustrates the market qualifiers and market winners of lean, agile and LeAgile paradigms. The LeAgile supply chain seeks to satisfy the most customers, with the lowest cost, as its market winner.

Table 2.1: the market qualifiers and market winners of lean, agile and LeAgile supply chain

	Lean	**Agile**	**LeAgile**
Market winners	Cost	Service level	Cost and Service level
Market qualifiers	Quality, Lead time, Service level	Quality, Lead time and Cost	Quality and Lead time

Achieving LeAgility means achieving the best of both lean and agile strategies. Figure 2.1 and Table 2.1 highlight that the lean and agile paradigms have different priorities to meet with different opportunities. Therefore, the challenges in the lean and agile combination are multiplied. Over the last two decades, supply chain researchers have sought to find opportune approaches to achieving a LeAgile supply chain. The following section discusses the four main approaches discussed in the literature for implementing supply chain LeAgility in the context of the current business environment.

2.2 LeAgility approaches

Four practical approaches were summarised by Christopher and Towill (2001) for combining lean and agile paradigms in one supply chain. They are known as the Pareto curve approach, separation of 'Base' and 'Surge' demands approach, the decoupling point approach, and the late customisation (or postponement) approach.

2.2.1 The Pareto curve approach

Organisations who manufacture or distribute a large range of products may find that the Pareto Law (80/20 or similar) can be applied to develop supply strategies (Christopher and Towill, 2001). The 80/20 rule can be applied on the basis of business analysis: 80% of overall volume will be generated from 20% of the total product line (Koch, 1998). The management strategies for the 20% and the remaining 80% should be very different. For instance, in some cases, 20% of the production volume is likely to be predictable and the lean paradigm may be exploited; on the other hand, the remaining 80% may be less predictable and the agile paradigm can be applied. Figure 2.2 illustrates a generic method by which the LeAgile strategy may be achieved by applying leanness for the 20% of predictable product, and agility for the remaining 80% less predictable products.

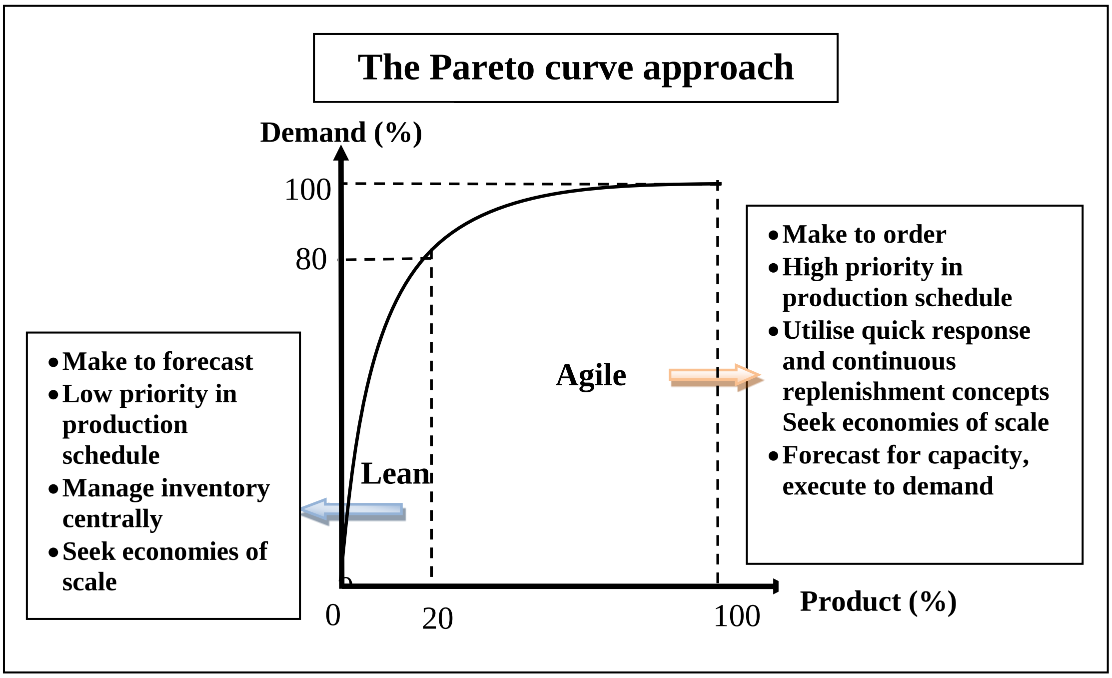


Figure 2.2: The Pareto Curve Approach to LeAgile (Source: Christopher and Towill, 2001)

In reality, the Pareto Law is very difficult to implement in supply chain management. It requires well defined market conditions and operational environments such as high levels of product variety and proportionate levels of demand in the product range. Furthermore, applying lean and agile strategies at the same time increases the complexity of operational management, which may cause the abuse of resources (Christopher and Towill, 2001).

2.2.2 Separation of “Base” and “Surge” demands

Another approach to combining lean and agile is known as the separation of “Base” and “Surge” demands. It also achieves supply chain LeAgility from the demand patterns by separating demand into “Base” and “Surge” elements. This strategy has been proven to be a successful approach for implementing a LeAgile strategy, particularly for the fashion industry (Goldsby *et al.*, 2006). Figure 2.3 shows a possible approach to separating the demand into “Base” and “Surge” (Christopher and Towill, 2001). The “Base” demand can often be predicated by using the demand history, whereas the “Surge” demand normally cannot. In this way, the smooth base demand is ideal for applying a lean paradigm, and the flexible agile paradigm can be used for the surge demand fluctuation. Some fashion companies like Zara won the supply chain advantages by focussing on reducing the cost of “Base” demand. More importantly, supply chain executives can deal with both “base” and “surge” demands either by separation in time (produce the “Base” stock in off-peak time) or in space (produce by production lines). However, the significant cost reduction in outsourcing and increasing visibility in transportations overcame these benefits (Christopher and Towill, 2001).

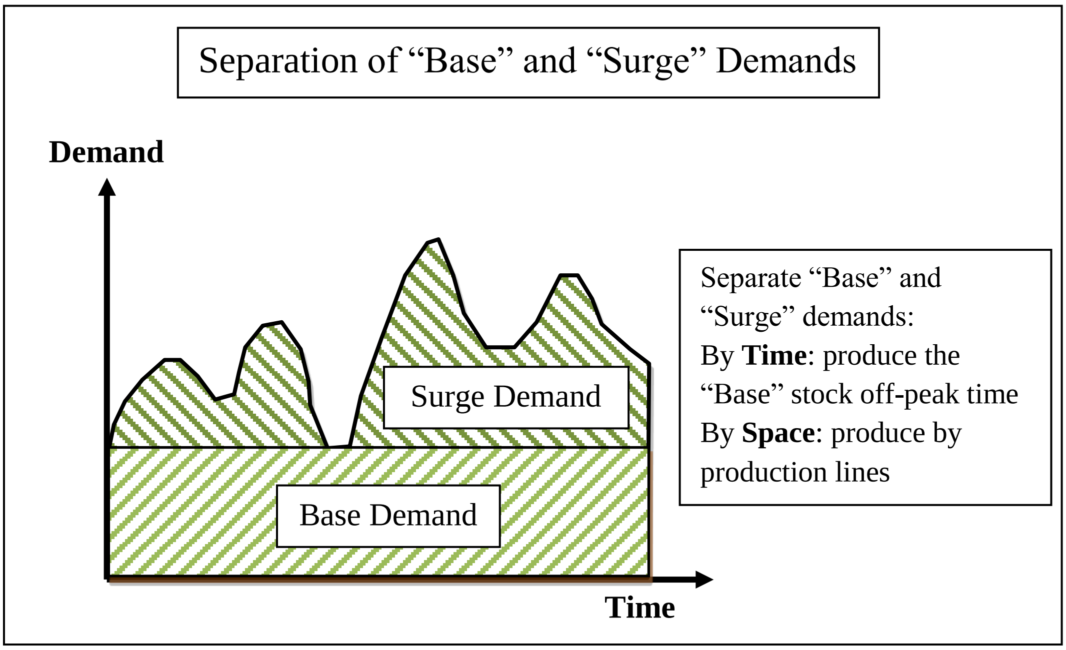


Figure 2.3: Separation of "Base" and "Surge" Demands (Source: Christopher and Towill, 2001)

2.2.3 The decoupling point approach

The most discussed LeAgile methodology in the literature is known as the decoupling point approach. The decoupling point is generally described as the point at which strategic inventory is held to deal with downstream demand variation; between order fluctuation and/or product variety and smooth product output (Mason-Jones and Towill, 1999; Christopher and Towill, 2000). The decoupling point acts as a strategic buffer, upstream from which point lean principles can be applied, and downstream from which agility is optimised (Mason-Jones and Towill, 1999; Rahimnia and Moghadasian, 2010). This is also sometimes known as the material decoupling point.

An information decoupling point can also exist, and is the real demand penetration point (Christopher and Towill, 2000). The original definition for the information decoupling point is the point in the information pipeline to which the marketplace order data penetrates without modification (Mason-Jones and Towill, 1999). It is the point where the forecast information and customer demand information meet. It is placed as far upstream as possible in order to enable as many members as possible to access real customer demand data, as shown in Figure 2.4. Usually through the implementation of Information Technology (IT), supply chain partners can access greater shared information such as inventory level, order size, and production status to support their decision making. The concept of visibility in this research is based on information sharing. It focuses on making the production and operational information available for all the supply chain partners.

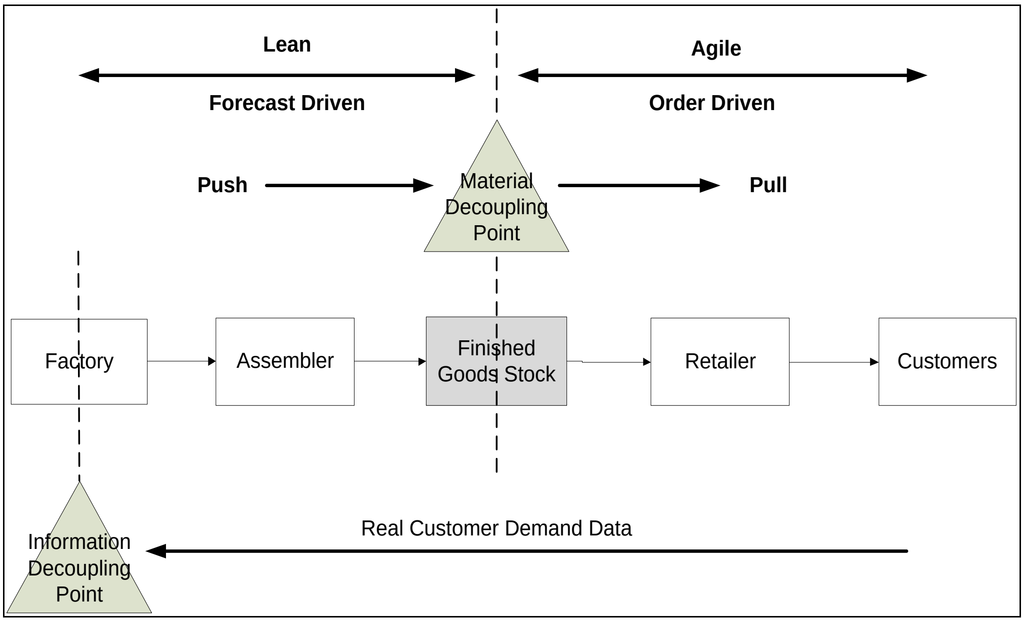


Figure 2.4: Comparison of material and information decoupling point position in a supply chain (Source: Mason-Jones and Towill, 1999)

The material decoupling point is critical as it will determine when and where to adopt lean or agile manufacturing techniques (Naylor *et al.*, 1999). Figure 2.5 illustrates the position of the material decoupling point in different supply chain strategies; of which "Assemble to Order" is generally recognised as an appropriate strategy to achieving LeAgility (Huang *et al.*, 2002). Previous research suggested that, in order to maximise performance, the material decoupling point should ideally be set close to the customer (Mason-Jones and Towill, 1999); on the contrary, the information decoupling point should be placed as far upstream as possible (Scholten *et al.*, 2010) to enable as many members as possible to access real customer demand data, and therefore to reduce supply chain uncertainty (Stevenson and Spring, 2007), as shown in Figure 2.5. Supply chain executives should not concentrate solely on improving one flow (e.g. the material pipeline), but should combine both flows (material and information) in order to improve the performance of the supply chain.

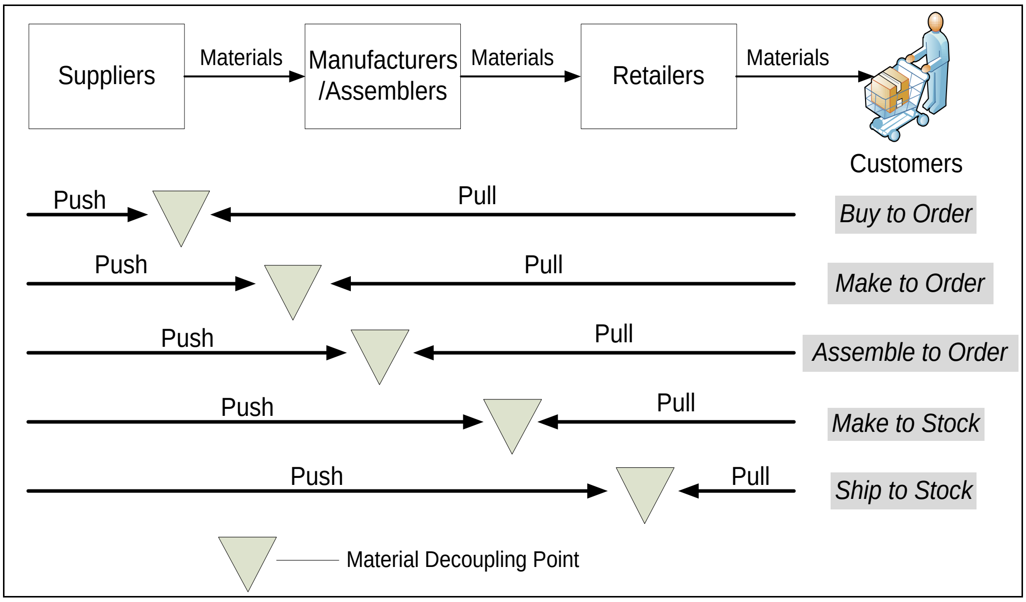


Figure 2.5: The material decoupling point positions in different supply chain strategies (Source: Naylor et al, 1999)

The concept of the decoupling point has been applied in many areas, and the results confirmed its ability to satisfy the customer needs in high variety environments (Donk, 2001; Huang *et al.*, 2002; Sun *et al.*, 2008; Rahimnia and Moghadasian, 2010). Donk (2001) developed a framework based on the concept of the decoupling point, which is useful in helping managers to make critical decisions about which products to make to order or stock in the food industry. Sun *et al.* (2008) extended the decoupling point research from a single supply chain to supply chain networks by applying multiple decoupling points to partition a supply chain network. Their results indicated that placing multiple decoupling points had positive effect on cost and customer delivery time reduction. A study from Rahimnia and Moghadasian (2010) suggested that implementing three decoupling points in a hospital supply chain reduced the lead time and costs, and resulted in more patients being assisted. However, one common issue revealed by their research is that it is very difficult to derive the correct and appropriate strategic inventory at decoupling points to balance the operational stability and the market requirement in both theory and practice. In addition, compared with other approaches, higher inventory costs are a common consequence for the decoupling point strategies.

2.2.4 Late customisation (postponement) approach

Late customisation (postponement) is linked to the decoupling point approach in the supply chain. In the late customisation approach, products are no longer fully completed for stock, or made to order, but produced part completed for stock, and customised for the respective market when ordered. Postponing the decoupling point nearer to the consumer increases effectiveness, since the supply chain is then better able to produce the products actually required by the market, and reducing the production of unwanted product types (Naylor *et al.*, 1999). Having a delayed configuration (or postponement strategy) allows a “mass customisation” strategy and this presents numerous advantages (Mason-Jones and Towill, 1999; Christopher, 2000): lower inventory, an increase in flexibility and forecasting accuracy. More importantly, postponement strategy is often viewed as an effective approach to achieve agility (Hoek, 2000; Graman and Sanders, 2009). However, LeAgility through postponement is only achieved as long as the supply chain focuses on waste elimination and fast responses.

2.2.5 The disadvantage of the four approaches

Previous research has demonstrated the impact of the decoupling point and postponement approaches on supply chain LeAgility (Hoek, 2000; Olhager *et al.*, 2006; Sun *et al.*, 2008; Graman and Sanders, 2009; Rahimnia and Moghadasian, 2010; Scholten *et al.*, 2010). However, the method with which to implement those methods was not clearly defined, since they may vary from situation to situation according to the extent to which leanness or agility is desired. Additionally, Table 2.2 highlights the research gap in the four LeAgility approaches in the context of the current business environment. This research addresses this gap by exploring supply chain visibility as an approach which offers advantages over those four approaches when creating a LeAgile supply chain, or can act as a tool to better enable these approaches.

Table 2.2: The advantages and disadvantages of the four approaches

LeAgility Approach	Contribution	Disadvantages
The Pareto curve approach	Lean management for 20% predictable product Agile for the other 80% less predictable products	Requires strict conditions to implement: high level of product variety and proportionate level of demand in the product range
Separation of 'Base' and 'Surge' demands	A successful approach to LeAgility, especially for fashion industry	Outsourcing and improved transportations can bring more benefits
The Decoupling Point	Lean for suppliers base and agile for customer side	High inventory level Hard to determine the appropriate decoupling point
Late Customisation	A flexible approach to agility	No lean Requirement to redesign products and the resulting supply chains

2.3 Supply chain visibility – A roadmap to LeAgile

Companies are under great pressure to eliminate disruptions from their supply chain in the current volatile business environment, however bad weather, labour disputes, shortages, defective materials and transportation issues can all be disasters for smooth operations. Better and quicker re-planning is the usual solution to these issues. Planning the best solution for every eventuality is nigh on impossible with complex operations, and secondly, the "best solution" depends on one subjective point of view. An individual member may well have to lose so that the whole system can win. The author believes supply chain visibility offers a much better solution, allowing the best decisions to be made, and thus the supply chain to be run to its best ability in a complex changing world.

2.3.1 What is supply chain visibility?

Visibility in general is defined as the fact of being easy to see according to the Oxford Advanced English Dictionary. In the context of Supply Chain Management (SCM), visibility means all seeing in supply chain. It is well accepted as a crucial constituent for effective supply chain management; however there is no precise definition of supply chain visibility which captures all its characteristics. Lamming *et al.* (2001) and Swaminathan and Tayur (2003) shared the same views about visibility; they emphasised the importance of information sharing and defined visibility as the ability to share information in the supply chain in real time. According to Francis (2008), supply chain visibility can be defined as "*the identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times for the events*". This definition focuses on describing the visibility of a hierarchy of entities and the linkages between them.

However, Penfield (2008) argued that visibility in supply chains is not just the track-ability of products (or parts of product) within the supply chain; it is the increase in available data that help analyse situation, make decisions, and determine strategies concerning improvements in the supply chain. To maximise the benefit of this data, information about business strategies and operations should be shared between partners (Eisman, 2008). Other aspects of supply chain visibility like real demand, quality of information, relatedness, and status are critical to enable effective visibility (Gustin *et al.*, 1995; Christopher and Towill, 2000).

There is always the risk of digital waste, information that does not directly relate to achieving the determined goals and metrics (Abbott *et al.*, 2005). Barratt and Oke (2007) highlighted that it is not only the information which matters but also the extent to which the information is accurate, useful, timely, trustworthy, and readily usable. Thus, real supply chain visibility requires that the applied information must be accurate and up-to-date for the critical activities and processes in the supply chain.

To sum up, some key characteristics of supply chain visibility are:

- Actual end customer demand
- Track and trace the transactions of the supply chain in real or suitable time intervals.
- Accurate and up-to-date information related to the critical activities and processes
- Sharing of business strategies and operation information between partners; alignment of business objectives

A supply chain visibility solution should capture all these characteristics to tackle the core issues of uncertainty and balancing cost/service level in a supply chain. A supply chain with good visibility should be able to respond effectively to the customer demand trends, leverage the root cause to quickly identify and solve the bottlenecks or issues; mitigate supply chain risks by monitoring and managing the KPIs after the relevant information is shared across the supply chain.

In order to do so, supply chain executives must know what types of information they need and by what means. The following section discusses the links between information sharing, visibility, and improved performance, and identifies the types of information needed to be shared for improving visibility.

2.3.2 Information sharing, visibility and improved supply chain performance

Many supply chain managers realise that supply chain need to be assessed for its performance in order to evolve an efficient and effective supply chain. The performance of a supply chain can be measured from strategic, tactical and operational levels by defining corresponding performance metrics. Many researches have been done to improve the supply chain performance. The majority of them in literature focus on investigating the impact of information sharing on improving supply chain performance.

1. Closs *et al.* (1997) investigated the effect of information sharing on logistics and argued that information sharing helps to better manage and coordinate the physical movement of the supply chain.
2. Dejonckheere *et al.* (2004) studied the impact of information sharing on the bullwhip effect, and suggested that sharing information at a higher level significantly reduces the bullwhip effect in supply chains.
3. A simulation study from Huang and Gangopadhyay (2004) investigated the effectiveness of information sharing and showed that it helps the distributors and wholesalers to reduce their inventory and backorders.

However, these studies did not investigate the link between sharing information and increased visibility.

4. Barratt and Oke (2007) identified visibility as the missing link of this research investigating the impact of information sharing on improving supply chain performance.
5. Holcomb *et al.* (2010) supported their statement and suggested a three-stage process to describe the linkage between information sharing and visibility:

    a) Visibility can only be achieved when the recipient believes the shared information is timely and accurate, useful and meaningful.
    b) The shared information needs to be incorporated into the recipient's decision-making process to allow better decisions to be made.
    c) Making better decisions logically leads to improved performance.

6. Sharing information through supply chain partners is generally agreed to be the key to improving supply chain visibility (Christopher and Lee, 2004).
7. The shared information can be classified in various ways. Huang *et al.* (2002) divided the production information into six categories: product, process, resource, inventory, order, and planning. Many studies have been published to identify the values and benefits of sharing this information.

8. Sharing the customer demand information is an effective approach to mitigate the bullwhip effect (Chen *et al.*, 2000; Croson and Donohue, 2003; Disney and Towill, 2003; Byrne and Heavey, 2006);
9. Sharing the order status for tracing can reduce payment cycles and improve the quality of customer service (Chen *et al.*, 2000; Byrne and Heavey, 2006);
10. Sharing forecasts has a positive influence on the products which have unpredictable demand (Angulo *et al.*, 2004; Byrne and Heavey, 2006).
11. Holweg *et al.* (2005) noted that sharing end customer demand caused a major improvement on the forecast at the supplier side.
12. In addition, the experiment by Byrne and Heavey (2006) showed up to 9.7% of total supply chain cost savings after demand information was shared completely.
13. Barratt and Oke (2007) identified that a high level of visibility on demand, process and inventory levels can bring a sustainable competitive advantage to supply chains;
14. Camerinelli (2005) noted that sharing financial information is very useful for developing partner relationships.
15. Additionally, Eisman (2008) and Omar *et al.* (2010) shared a view that sharing information of operations and business strategies across supply chains would increase supply chain visibility and improve performance.
16. Holcomb *et al.* (2010) argued that improving visibility on transportation would lead to cost reduction.

Table 2.3: Shared information for improving visibility

	Category	**Shared Information**
Product Information	Process	Lead time, delivery, set up time (Closs *et al.*, 1997; Huang *et al.*, 2002)
	Production	Production structure (Barratt and Oke, 2007)
	Inventory	Inventory level (raw material and finished goods) (Huang and Gangopadhyay, 2004; Barratt and Oke, 2007), backorders (Byrne and Heavey, 2006), service level (Byrne and Heavey, 2006)
	Resource	Capacity (Huang *et al.*, 2002)
	Order	End customer demand, orders (Chen *et al.*, 2000; Croson and Donohue, 2003; Disney and Towill, 2003; Byrne and Heavey, 2006)
	Planning	Forecast, centralised forecast, order Schedule (Angulo *et al.*, 2004; Byrne and Heavey, 2006; Eisman, 2008; Omar *et al.*, 2010)
Operational Information	Order	Order status (Chen *et al.*, 2000; Byrne and Heavey, 2006)
	Production	Operational status (machine breakdown, scrap rate) (Barratt and Oke, 2007; Eisman, 2008; Omar *et al.*, 2010)
	Process	Delivery status (late delivery) (Closs *et al.*, 1997; Holcomb *et al.*, 2010)

These discussions and observations addressed this question: what types of information should be shared to improve supply chain visibility? In order to gain the most benefits through sharing information, this research has summarised the relevant information to be shared for improving supply chain visibility in the literature as shown in Table 2.3. These types of information are shared in the simulation of this research to investigate the impact of visibility on improving supply chain LeAgility.

2.3.3 The issues related to visibility in supply chains

Imagine a trip to your local shop to buy goods and bring them home. You could try to complete the trip with your eyes shut, relying on your trip plan with directions from your sat nav. This situation of no visibility is unlikely to be successful, but many types of supply chain planning and operation rely on just this. The environment for the trip is just too complex to totally predict in advance. Or you could complete the trip with your eyes wide open all the time, full visibility! This guarantees great agility and responsiveness, but is demanding in resources and may well tire you unnecessarily. So you need to decide what rate of eye blinking you should adopt for this trip, and whether it will be the same for all parts of the trip, and for other similar trips. The blink rate trades off agility against leanness. If we then say that a team of people have to complete the shopping trip, each carrying out one part of the journey, the complications multiply. In terms of visibility, the team need to know what is actually required (demand visibility) and what the current situation is (operational visibility). How this information is transmitted and acted upon determines the overall success of the supply chain.

Although supply chains have already become leaner, there are still lost opportunities when disruptions happen. The issues related to visibility in supply chains can be grouped into these four areas:

1. goods in the wrong location or not available; transportation issues; lack of collaboration in the supply chain network (Sterling-Commerce, 2009);

2. lack of visibility in the order, shipments, inventory and transactions (Sterling-Commerce, 2009).
3. Improved visibility encourages and enhances collaboration through trust building.
4. Logically, the best way to infuse trust is to let partners understand what is going on in other parts of the supply chain.

The next section establishes the value of visibility by sharing demand and operational information.

2.3.4 Establishing the value of visibility

As discussed before, supply chain members need to know what the actual demand is, as well as the current situation, in order to make better decisions. Therefore, with respect to visibility, the author suggests the following two requirements in the context of a supply chain:

1. **Demand Visibility**: seeing what is required

   Visibility of demand allows each partner to access real demand information in real time. This means giving each partner access to demand information from as close as possible to the source, plus their partners' interpretation of the resulting requirement for themselves.

2. **Operational Visibility**: seeing what is the current operational situation Shared operational information allows a better assessment of risk by each partner, resulting in better overall optimisation. It also allows better re-planning in the event of an unexpected disturbance in operations.

Increasing visibility in customer demand and operations allows the supply chain to achieve two ultimate objectives: to improve customer satisfaction, and to increase efficiency and effectiveness. Information technology (IT) plays an important role in assisting supply chain managers to achieve these goals. The next section examines the role of IT for implementing supply chain visibility.

2.3.5 Technologies for implementing visibility

The values of supply chain visibility are extensively accepted. A survey from Global Chief Supply Chain Officer Study (IBM) interviewed nearly 400 senior supply chain managers in 25 countries and indicated that 70% of them ranked supply chain visibility as their top challenge and the second priority after cost containment (Butner, 2010). However, most of supply chain managers still have difficulties to achieve visibility even information nowadays is abundant and easier to obtain than ever. So what is obstructing visibility deployment? The high cost of IT may be one barrier.

Many researchers have shown a growing interest in identifying the impact of information technology (IT) on supply chain management (Iacovou *et al.*, 1995; Lee *et al.*, 1997; Yu *et al.*, 2001; McCormack and Kasper, 2002; Simatupang and

Sridharan, 2002; Disney and Towill, 2003; Lee and Kim, 2006; Pereira, 2009; Holcomb *et al.*, 2010; Omar *et al.*, 2010; Wang *et al.*, 2010a). IT allows real time information sharing through supply chains, and facilitates the communications between suppliers and customers. Simatupang and Sridharan (2002) stated that IT such as the internet, software applications and decision support systems allows supply chain managers to improve visibility in three areas:

- Customer demand (price, customer information, location, quantity)
- Resource planning (forecasting, product scheduling, transportation, inventory, location, lead time, capacity)
- Contract status (ordering, invoicing, price, payment, status tracking).

Technologies such as Electronic Data Interchange (EDI) and Vendor-Managed Inventory (VMI) have demonstrated their abilities in improving demand visibility. Iacovou *et al.* (1995) developed a framework of EDI for small businesses and demonstrated that EDI could provide a quality of information to improve customer service and operation efficiency, and reduce cost on transaction. EDI can also improve the delivery performance of suppliers, which then eventually improves the supply chain performance (Lee *et al.*, 1997). Yu *et al.* (2001) studied the benefits of information sharing and suggested that using EDI to support VMI for inventory management does not only reduce the bullwhip effect, but also improves supply chain performance in terms of inventory and cost reduction.

VMI is often considered to be an inventory planning and fulfilment technology. In a VMI system, suppliers are allowed to access the buying company's database to monitor and maintain inventory at an agreed level. VMI can better mitigate the bullwhip effect than a traditional supply chain, since demand and inventory information is shared between suppliers and customers. A simulation by Disney and Towill (2003) showed that VMI performed better at responding to volatile changes in demand. In addition, Yu *et al.* (2001) noted that VMI enables suppliers to speed up their decision-making on inventory control which results in performance improvement.

A study by McCormack and Kasper (2002) investigated IT from the perspective of the Internet. Using internet technology has significantly enabled the success of Vender Managed Inventory (VMI), and Collaborative Planning, Forecasting and Replenishment (CPFR). Holcomb *et al.* (2010) noted that internet technologies such as VMI, CPFR, Materials Requirement Planning (MRP) and Enterprise Resource Planning (ERP) integrate and coordinate various phases of the supply chain resource planning in real time which improves supply chain visibility.

It is believed that a high investment in IT seems to cause an obstacle for information sharing (Omar *et al.*, 2010). Internet technology offers a lower cost and rich content method to share information through supply chains. O'Donnell and Glassberg (2005) suggested that web-based technology represents a relative low investment in hardware and software, and less modification of the core system, as compared with EDI. More importantly, web-based technology such as web services (WS) and Service Oriented Architecture (SOA) addresses some of the issues of MRP and ERP, by offering standardised protocols which allow different applications to interact (Lee and Kim, 2006). In SOA, services are online and accessible to all supply chain members. In this way, customer demand and current inventory level are visible for all members which result in improved supply chain performance (Pereira, 2009). In particular, services in SOA can be accessed via computers and mobile phones, allowing information about supply chain disruptions to be sent in a timely fashion and automatically, via emails or messages, by monitoring supply chain events (Folinas *et al.*, 2006). However, Guah and Currie (2005) argued that security, reliability and vendor hype issues obstruct the implementing of web services. Butner (2007) added that implementing SOA requires a technological redesigning of a company’s IT architecture.

Technologies like simulation modelling, Radio Frequency Identification (RFID) and Business Intelligence (BI) are considered to be promising technologies to complement supply chain management systems (Hugos, 2006). According to Hugos (2006), these technologies can integrate with the existing system and collect data to improve its data visibility. For instance, Goldsby *et al.* (2006) modelled the lean, agile or LeAgile strategy and indicated that simulation modelling can better address "what if..." questions, by offering a comparison of alternatives, which helps supply chain managers understand the realities of each strategy before committing significant resources. Additionally, technologies such as barcode and RFID make it possible for companies to track and trace material or product flow at different stages in a supply chain. A simulation by Wang *et al.* (2010a) compared the performance of RFID-enabled and non-RFID supply chains and demonstrated that using RFID improved the overall supply chain performance via a reduced bullwhip effect, 35.43% inventory reduction, and 61.36% increase of inventory turnover. However, Davenport and Brooks (2004) argued that the cost of implementing RFID is much higher than that of the barcode labels.

The Executive Information System (EIS) (also known as a dashboard) provides the current supply chain status to supply chain managers based on pre-defined key performance indicators (KPIs). Lungu *et al.* (2006) described a dashboard as a business intelligence (BI) tool which facilitates and supports the information and decision-making needs of high-level executives by collecting, analysing and visualising relevant internal and external information.

A report by Aberdeen Group summarised the current IT systems for enabling visibility in 128 Best-in-class global companies (Heaney, 2012), as shown in Figure 2.6. However, the IT systems such as ERP, EDI, WMS, and BI, used by these Best-in-class companies are too costly for Small and Medium Enterprises (SMEs).

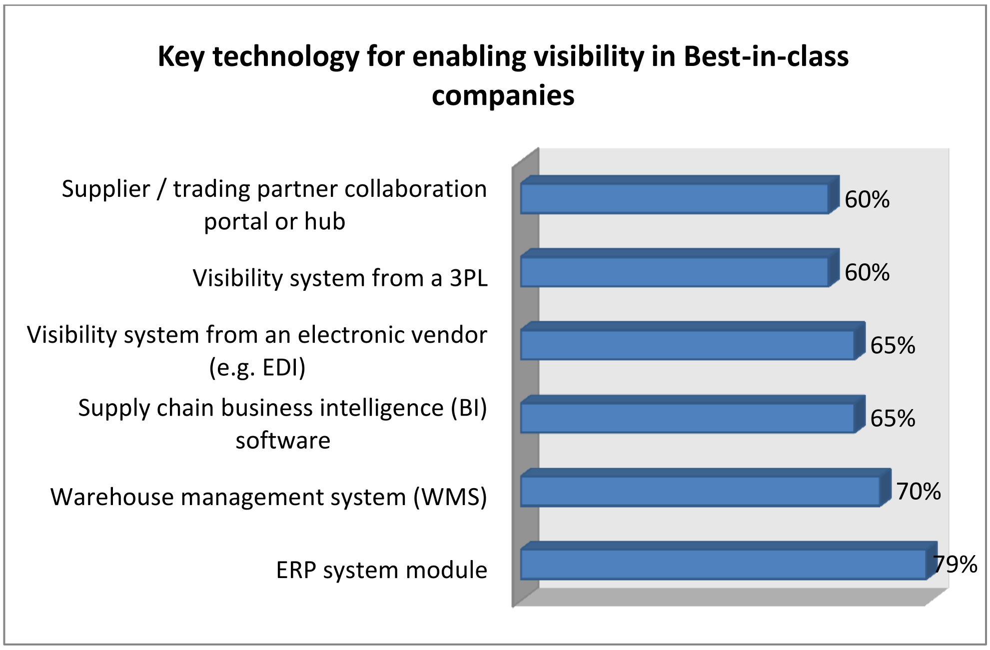


Figure 2.6: Technology for enabling visibility in Best-in-class companies (source: Aberdeen group, Heaney, 2012)

The visibility system used in this research demonstrated a relatively low cost web solution for SMEs to improve visibility. This visibility system was designed based on some free Google products. The key information related to supply chain status was shown in a dashboard by red (urgent), amber (attention), and green colours (fine) coding, which can be customised by defining different KPIs and their limits. A notification system automatically sent prompt notices to supply chain managers via both dashboards and emails/messages when the status changed. Supply chain managers were then able to respond to the change and made decisions based on the current supply chain status. Chapter 4 describes the system design in detail.

2.4 The difference between the visibility approach and the decoupling point approach

The main principle of the supply chain visibility approach for improving LeAgility is information sharing. It differs to other approaches since it does not replace existing supply chain management systems. The difference between the supply chain visibility approach and the decoupling point and postponement approaches is illustrated in Figure 2.6. In the decoupling point approach, supply chain LeAgility is achieved by improving leanness upstream through process standardisation, smooth level scheduling and waste elimination (Mason-Jones and Towill, 1999), and simultaneously increasing agility to quickly respond downstream demand variation. The supply chain visibility approach enables LeAgility by sharing customer demand and operational information with all supply chain partners (upstream and downstream) in a virtual supply chain network. Leanness is achieved through a continuously accurate forecast, better production schedule and coordination to reduce inventory and cost; and agility can be achieved through rapid responses to the customer demand, and improved flexibility to manage the disruptions.

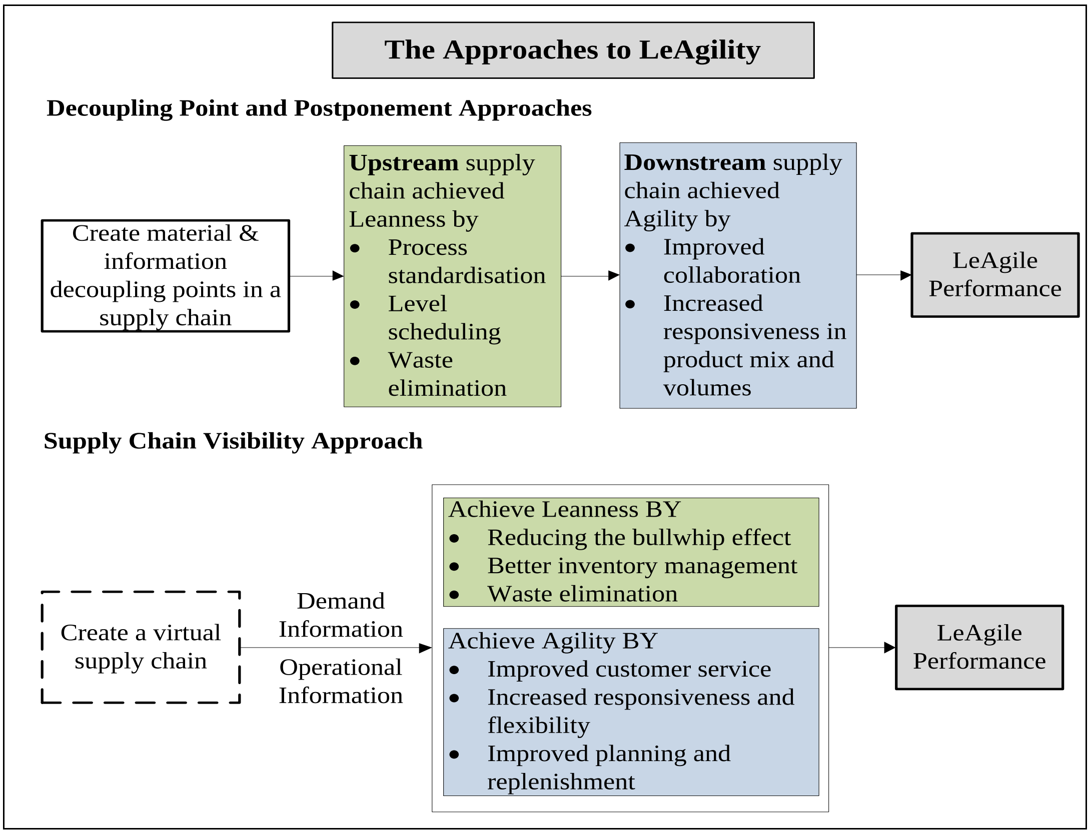


Figure 2.7: The difference between the supply chain visibility approach and the decoupling point approach

2.5 Summary

The research gap was identified by discussing the disadvantages of the four approaches for achieving LeAgility in literature. The supply chain visibility approach was then proposed as a better solution to improve supply chain LeAgility. Previous research suggested that increasing information visibility improves supply chain performance (Simatupang and Sridharan, 2002; Fliedner, 2003; Barratt and Oke, 2007; Bartlett *et al.*, 2007; Holcomb *et al.*, 2010). However, it has not shown the clear correlation of increased visibility and improved supply chain performance. The author explores this correlation through a hybrid simulation which is introduced in the next chapter.

3

Research Methodology

The major objective of this research is to investigate the impact of supply chain visibility on improving supply chain LeAgility. In order to fulfil this objective, the research was divided into three phases. The first phase was to identify the research gap in previous published work. The second phase was to observe the behaviour of a typical supply chain with differing degrees of visibility. The third phase was to explore the correlation between increased visibility and improved supply chain LeAgility by analysing the results from phase two through a performance measurement framework, and to evaluate their business implications.

3.1 Research method

The most discussed research methods in supply chain management are case study, survey and simulation/modelling. Table 3.1 discussed their advantages and disadvantages in this research. A simulation approach was chosen as the research method to evaluate the effect of visibility. Simulations are recognised as an effective and well-established method for collecting primary data in supply chain management. They have the ability to reproduce the "*features, appearance, and characteristics*" of a real business or management system, to implement business models and obtain relevant data in a shorter time through time compression (Render *et al.*, 2008; Stefanovic *et al.*, 2009). More importantly, they allow "what if" analyses to assist in decision-making, by the ability to control different variables (Stefanovic *et al.*, 2009).

Table 3.1: the comparison of the three research methods in this research

Research Methods	Advantages	Challenges
Case study (Gable, 1994; Voss et al, 2002)	• Can follow well established framework • Good to develop and test new theory and ideas	• Time consuming • The results can be high impacted by the selected cases • Not necessarily representative or generalisable
Survey (Gable, 1994; Zhang, 2000)	• Large simple • Quantitative data	• Time consuming • Difficult to encourage participant response • The results show what the participants think and believe but no necessarily how they behave • Difficult to maintain the accuracy range and confidence level
Simulation /model (Render et al., 2008; Stefanovic et al., 2009)	• Consuming less time • Variable control • What-if analyse • Good to explore the relationship between visibility and supply chain performance • Quantitative data	• Difficult to build a simulation tool/model • Results need to be verified • Simulation errors

3.1.1 Three types of simulation in supply chain management

There is little consensus on the term ‘simulation’ in the literature. Many authorities tend to place role playing and gaming within the context of simulation. The following summarises the three simulation terms which are used frequently in supply chain management: computer simulation, role playing and games.

3.1.1.1 Computer simulation

Physical simulation has many cost-related and technical limitations when simulating a supply chain (Chang and Makatsoris, 2001; Stefanovic *et al.*, 2009).

Many industry solutions such as MRP and ERP, which provide many benefits in supply chain management, can be an ideal solution to simulate a supply chain; however, it is too expensive to use them in supply chain simulations. A computer simulation is an ideal method to simulate a supply chain, due to its flexibility in dealing with the complicated variables suggest a number of experts (Jia and Zuo, 2010).

Computer simulations can model supply chain processes, especially information flows, financial flows, and material flows, to evaluate and predict supply chain performance prior to system implementation. They can also support decision-making by implementing a 'what-if' analysis to compare various alternatives without interrupting a current system (Thierry *et al.*, 2010). The simulation is usually designed as an interactive tool to support decision-making in supply chain management. However, it is very difficult to simulate human factors in a computer simulation. It is hard to ignore the human motivations and actions in a real supply chain. Since these human factors can totally dominate supply chain operations often role playing simulations are used to simulate this behaviour.

3.1.1.2 Role playing

Role playing involves participants immersing themselves in a simulated business environment by playing the role of a business or process owner (Feinstein *et al.*, 2002). It requires the participant to follow a set of rules that define the current situation, and to make decisions after interacting with others. In this way, the simulation can better emulate human activities to evaluate or solve a problem in a supply chain. However, the results from these simulations could be very subjective since each decision relies on the interactions of other participants who often exhibit learning curves and learning effects well as many other types of human interaction behaviour. In addition, a lack of control during the simulation, and high cost are often major limitations to implementing a role playing simulation.

3.1.1.3 Games

The Beer Game is the most famous simulation game in supply chain management. It was created in the 1960s by the Massachusetts Institute of Technology (MIT) to show students some key principles of supply chain operation (Goodwin and Franklin, 1994). It has been employed in many areas in supply chain management, and has proved to be a very effective and powerful tool to help supply chain managers to understand supply chain interdependencies.

According to Feinstein *et al.* (2002), most management games are round-based or turn-based. In these games, the participant is required to form strategies based on the current situation in the first round; in a new round, the strategies are normally modified, based on the changed variables. The games normally repeat for a number of times to generate a result. The reward generally is given to the most profitable participants.

It is very difficult to simulate a dynamic business environment in these types of game, since they are normally turn-based. Therefore, decisions are usually made based on the result of the last round, not on the situation in the current round. It is difficult for the participants to appreciate how their decisions have interacted with the others until a new round. Furthermore, it can be too complicated to create a "what-if" analyse in the game simulation (Feinstein *et al.*, 2002).

In order to better evaluate the effect of visibility on supply chain LeAgility, tight control on variables and "what-if" capability are required to test many different scenarios. None of these three types of simulation are fully effective in this case. Therefore, a hybrid simulation model, which combined the advantages of role playing games and computer simulation, was designed to replicate the business environment and incorporate the human factors that appear in real supply chains. The hybrid simulation model was partly used to help the participant to learn to manage real time data in order to optimise their decision making. It was possible to include "what-if" analyses to test different scenarios in a shorter period with a lower error level using this approach. In addition, the 'learning effect', which can be recognised both as a weakness and an asset of a role playing simulation, may be controlled by switching or not switching user roles.

The debate about using the hybrid simulation or computer simulation is ever-present in this research. Good computer simulations require clear hypotheses with simulators being designed accordingly. It is necessary to design and control each variable in order to output valid results. Since the output of the simulation in this research is stochastic, an experimental design is required firstly to test all the hypotheses that are developed. In this way, the result will show the impact of visibility on supply chain performance in a laboratory. However, the fact is that real supply chains are controlled by humans, and human decision making activities cannot be realistically simulated by any computer. This is a major reason for choosing a hybrid simulation.

3.1.2 Simulation objective

The objective of the simulation is to collect evidence of the impact of information visibility on improving supply chain LeAgility. Several sub-objectives are derived to achieve it:

1. The impact of enabling supply chain visibility of customer demand on improving supply chain LeAgility
2. The impact of enabling visibility of supply chain operations on improving supply chain LeAgility
3. To identify the advantage of the supply chain visibility approach

3.1.3 The process of simulation design

The processes for designing the simulation are shown in Figure 3.1. There were three stages in simulation design: simulation model design, scenario design, and performance measurement framework design. The simulation model design defines the supply chain structure and its parameters and variables, the triggers for monitoring and measuring, and the IT support required. The outcome of the simulation model design was tested and its feedbacks evaluated and adapted to improve the simulation model design. The scenario design defines the different scenarios used in the three experiments. Each scenario represents a specific information sharing configuration (visibility level). If an error occurred in the experiment, the process stopped and started again from the beginning of the current round, in order to avoid the impact of cumulating mistakes on supply chain performance. The performance measurement framework design defines the performance measures used to measure supply chain LeAgility. The detailed simulation design is described in chapter four.

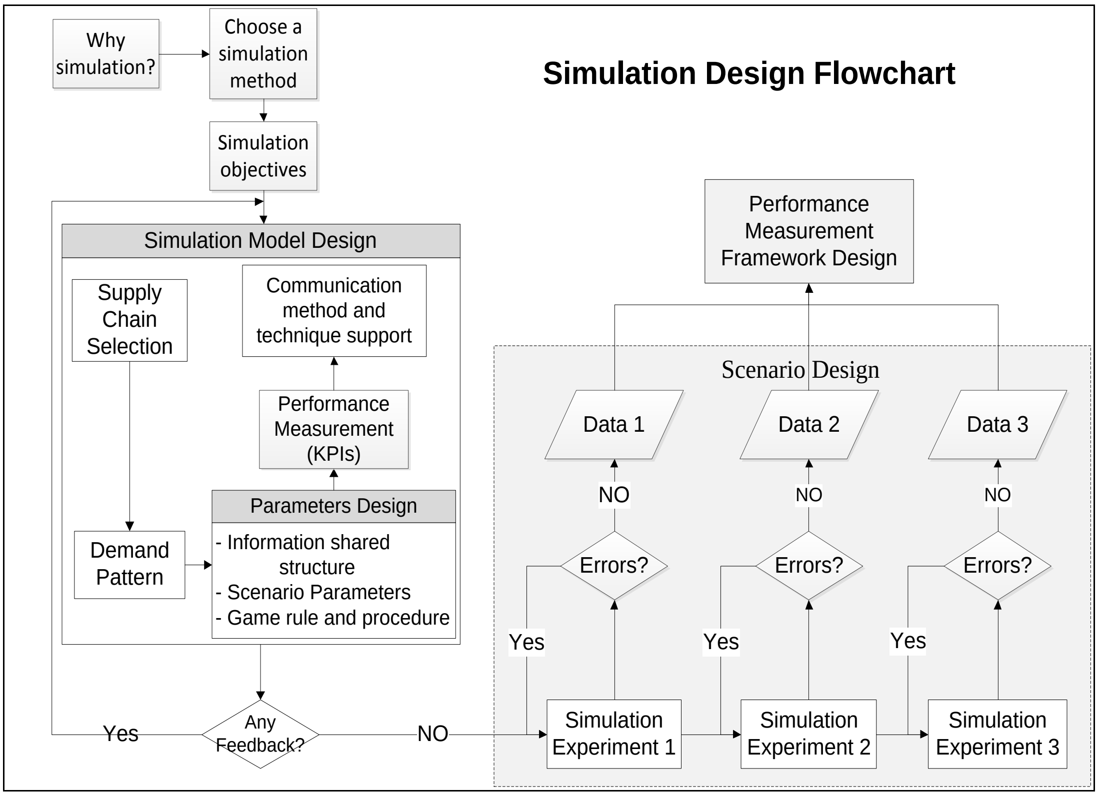


Figure 3.1: The simulation design flowchart

3.1.4 Simulation Model Design

In the simulation, participants acted as the owners of factories or processes, and tried to maximise their profits based on the information they had. They were able to access different information in different scenario configurations. The scenarios were designed based on the level of shared information and information sharing frequency (heartbeat). The computer simulation acted as a decision support system which helped the owners understand their own and their partners’ status according to the scenario configurations. For instance, the participants were able to “see” data from the entire supply chain in the full visibility scenario.

3.1.4.1 Participants’ selection

An effective team is the key for the success of any project. Based on the specifications of the role playing simulation, this research used Nicky Hayes’s role-definition approach to select the participants. Building a team focused on this approach aims to clarify the role of each member, the responsibilities to each other and the norms of the whole team (Hayes, 1997). So the team can operate effectively and efficiently because each member has a clear understanding of their roles and responsibilities.

The participants were selected according to their background knowledge, communication skill and teamwork which are the minimum requirements for the simulation. In order to ensure each participant had the relevant background for this research, the selection targeted the MSc students in Supply Chain and

Logistics Management from Warwick Manufacturing Group in 2009 and 2010. Six candidates were chosen based on their understanding of the topic, their communication skills, and the willingness to work in a team. They were involved in the simulation design and test once they understood the topic; and their feedbacks were considered to improve the simulation design.

3.1.4.2 Supply chain selection

The supply chain used in the simulation was adapted from the well-documented case study of the Hewlett Packard Deskjet printer global supply chain (Kopczak and Lee, 2001; Simchi-Levi *et al.*, 2003). The original supply chain could be viewed as a typical vertical integrated five-echelon supply chain with four key suppliers or manufacturers and three distribution centres (see Figure 3.2a).

This five-echelon supply chain had been generalised to a typical four-echelon supply chain, which includes suppliers, OEM, distributors/retailer and end users (see Figure 3.2b). There are three reasons for the supply chain selection:

a. The five-echelon supply chain in Figure 3.2a was modelled from the Hewlett Packard Deskjet printer global supply chain (Kopczak and Lee, 2001; Simchi-Levi *et al.*, 2003).
b. The supply chain model had been modified to a four-echelon supply chain due to the time constraints and the limitation of the participants. It kept most complexity of the original supply chain to evaluate the effect of visibility by erasing two suppliers and combining two suppliers; the

production variety and distribution centres were also reduced to two because of the low sale data (Figure 3.2a). It was a very typical supply chain which captured all the functions of the original supply chain. However, the author designed complex variability in the simulation scenarios to fully examine the capability of visibility to respond to a changing business environment. Figure 3.2b shows the modified supply chain structure which simulated four of the five supply chain echelons, with two different products (A and B) customised for two different markets (EU and US).

c. The case study described a typical make-to-stock supply chain, and proposed an approach to solve the supply chain issues by adopting the decoupling point strategy and postponing the assembling process to distribution centres. As a result, it is an ideal case study for this research in order to compare the supply chain visibility approach and the decoupling point and postponement approaches.

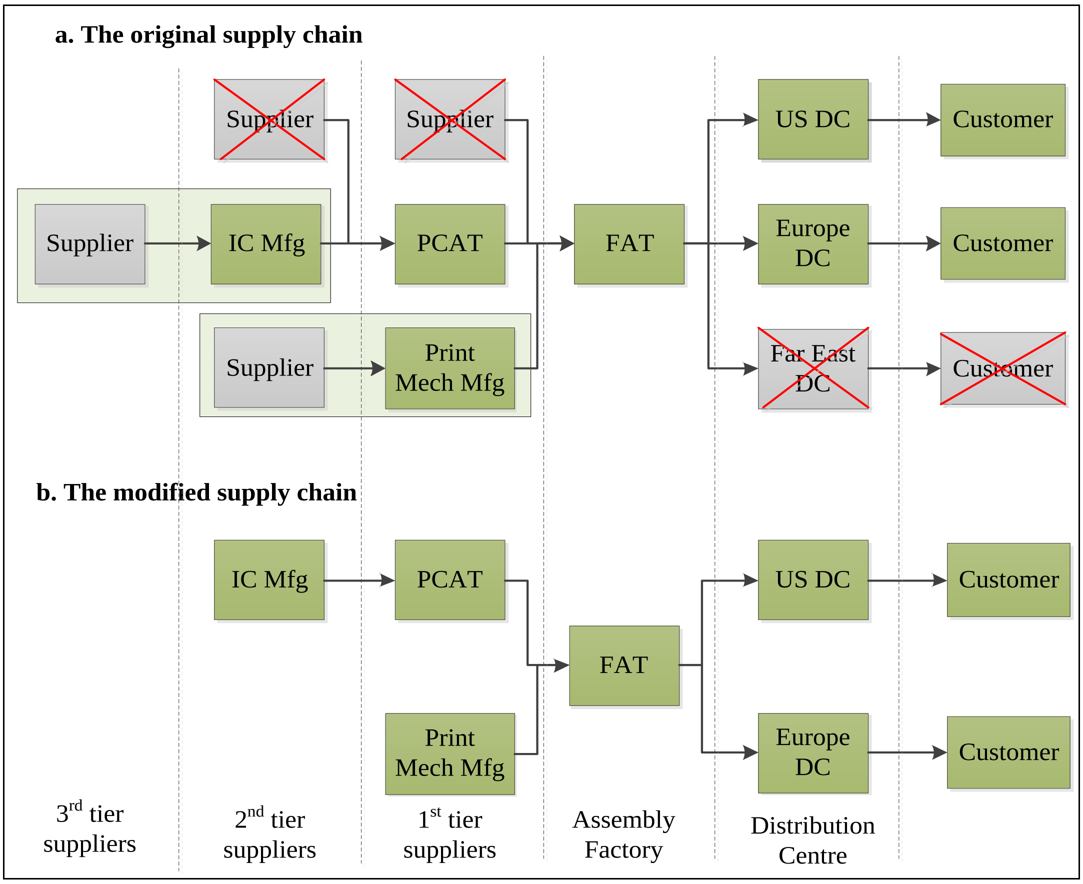


Figure 3.2: Supply chain selection

3.1.4.3 The types of information sharing and information sharing structure

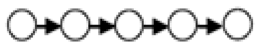
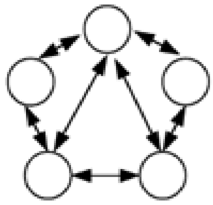
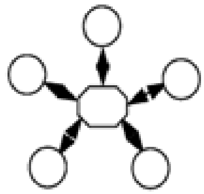
An appropriate information sharing structure is vital to the success of of the research experiments. The types of information sharing applied in these simulations have been discussed in Chapter 2.3.2. Table 3.2 illustrates three types of information sharing structures: sequential, reciprocal, and hub-and-spoke (Kumar and Dissel, 1996; Hong, 2002; Liu and Kumar, 2003).

1. The **Sequential** information sharing structure is very common in the traditional supply chains and third-party logistics (3PL). Information flows one by one from downstream to upstream in one direction. The output of one partner will flow into the next partner as the input (Liu and Kumar, 2003).

2. The **Reciprocal** information sharing structure is more complex than the sequential information sharing structure. Information flow is two-way, and each partner can share information with multiple partners. It usually requires the supply chain partners to synchronise their information in order to reduce the inconsistencies caused by the multiple information flows. A VMI (Vendor Managed Inventory) system is the best example for this information sharing structure.

3. The **Hub-and-Spoke** information sharing structure shares information to all partners through a centralised e-hub which usually is implemented by web services. This centralised e-hub synchronises and coordinates information about each partner, then shares them to all supply chain partners. It is the foundational architecture of many CPFR (Collaborative Planning, Forecasting, and Replenishment) systems. Nowadays, with the help of cloud service, hub-and-spoke information sharing structure is used as the architecture to design the visibility solution for many companies, such as GXS and IBM.

Table 3.2: Information sharing structures (Source: Liu and Kumar, 2003)

	Sequential	Reciprocal	Hub-and-Spoke
Information Sharing Structure			
Information Flow	One-way information flow between neighbouring partners	Two-way, multiple information flows among partners	Two-way, centralized e-hub
Applications	Traditional supply chains and 3PLs	VMI (Vendor Managed Inventory)	GXS, IBM

A study from Liu and Kumar (2003) compared information sharing structures and information flow in four different supply chains: VMI, CPFR, 3PL, and supply networks; the results indicates that the hub-and-spoke structure is more appropriate for supply chain networks to increase visibility and improve coordination. Unlike the sequential and reciprocal information sharing structures, the central database in the hub-and spoke structure allows supply chain partners to access shared information synchronously. Therefore, the hub-and-spoke is adopted as the information sharing structure in this research.

3.1.4.4 Parameters and variables

The parameters and variables of this simulation are divided into seven groups: demand pattern, lead time, capacity, forecasting, inventory policy, unexpected events, and costs management. The details of these parameters and variables are introduced in Chapter 4.2.

3.1.4.5 IT support

To implement a hub and spoke information sharing system for the simulations a open source set of Google products (Google Docs, Google Wave and Google Sites) were selected to build a visibility system. The reasons for using these Google products are their functionalities:

1. Cloud service. Google Docs is a free online office tool which includes Word, Spreadsheet, Presentation, Drawing, etc. Most importantly, Google spreadsheet has the capability to become a cloud (shared) database.
2. Real time collaboration. Google Docs can be shared with anyone with internet access. Any change to the documents can be seen in real time.
3. Better communication. Google Wave is a live application for real-time communication and collaboration. It has the ability to manage one-to-one communication and group communication at the same time through different channels.
4. Google Sites is used as a project workspace in the simulation. It acts as a data entry and display portal for the participant.
5. Easy access from computers and mobile devices.

In the simulation, inventory data, manufacturing data, order and sale data are recorded automatically into a central database created by Google Docs. The participants can view different data on their dashboard according to the scenario configurations. Google Wave was used to manage all the communication and to share files during the simulation. The details of the design are presented in chapter 4.4.

3.1.4.6 The sequence of the simulation

Like other role playing simulations, this simulation defined its operation sequences in order to synchronise the supply chain activities.

Stage one: load the supply chain

- Generate the forecast based on the history data
- Start the production to build the stock

Stage two: normal process

- Order raw material
- Arrange production
- Receive orders from customers
- Delivery the orders to customers
- Update forecast
- Finish the process after making the raw material order for the following week

3.1.5 Scenario design

With respect to visibility, the authors identified the following three experiments in the simulation to address the research question:

- **Demand visibility experiment:** seeing what is required

  Previous research has suggested the effect of sharing end customer demand on improving supply chain performance (Chen *et al.*, 2000; Croson and Donohue, 2003; Disney and Towill, 2003; Holweg *et al.*, 2005; Byrne and Heavey, 2006). Visibility of demand allows each partner to access real demand information in real time. This means giving each partner access to demand information from as close as possible to the source, plus their partners' interpretation of the resulting requirement for themselves.

- **Operational Visibility experiment:** seeing what is the current situation

  It is generally agreed that sharing information of process and operations across supply chains would increase supply chain visibility and improve performance (Eisman, 2008; Omar *et al.*, 2010). Shared operational information allows a better assessment of risk by each partner, resulting in better overall optimisation. It also allows better re-planning in the event of an unexpected disturbance in operations.

- **Decoupling Point & Postponement experiment:**

  The decoupling point and postponement approaches have been demonstrated as effective methods to improve supply chain LeAgility (Hoek, 2000; Olhager *et al.*, 2006; Sun *et al.*, 2008; Graman and Sanders, 2009; Rahimnia and Moghadasian, 2010; Scholten *et al.*, 2010). By comparing to the decoupling point and postponement approaches, supply chain visibility approach can be identified as an approach which offers advantages over those two approaches for improving supply chain LeAgility, or can act as a tool to better enable these approaches.

The scenarios for each experiment were designed based on shared information in five dimensions: forecast, inventory, real demand, operational information and heartbeat. The heartbeat defined the information sharing frequency in each scenario. The detailed scenario configurations are shown in chapter 4.5.

3.1.6 Performance measurement framework

Measuring supply chain performance is critical for supply chain executives to monitor, understand and improve their supply chains. Supply chain performance can be measured in various ways depending on the measurement purposes. The author reviewed and analysed thirteen papers in order to understand what frameworks have been adopted recently, their measurement perspectives and measures. The author’s goal was to develop a robust performance measurement framework for this research. Table 3.3 classifies the performance measurement frameworks and their performance measures from the reviewed papers. The Supply Chain Operations Reference (SCOR) model developed by the Supply Chain Council was the most referenced framework in the papers since 2004. Performance measures such as bullwhip effect, inventory level, service level, inventory cost, total cost, delivery, sales, fill rate, flexibility and reliability were the major measures in performance measurement system.

Table 3.3: Performance frameworks and their measures in literature

No.	Paper	Performance Measurement Methods	Performance Measures
1	Cachon and Fisher (2000)	Compare performance of inventory by Modelling/Simulation	Inventory cost, Penalty cost
2	Chen *et al.* (2000)	Measure inventory performance by Modelling/Simulation	Inventory, Bullwhip Effect
3	Li *et al.* (2001)	Measure performance of inventory and order fill rate by Modelling/Simulation	Inventory, fill rate
4	Yu *et al.* (2001)	Measure the bullwhip effect by Modelling and case study	Bullwhip Effect (inventory level and cost)
5	Gunasekaran *et al.* (2004)	Self-develop framework (**SCOR**) focused on the performance metrics of Plan, Source, Make/assembling, Delivery	Customer service, cost, delivery
6	LockamyIII and McCormack (2004)	**SCOR** framework Version 4.0 (Plan, Source, Make, Delivery)	Questionnaires on Plan, source, make, delivery
7	Gunasekaran *et al.* (2005)	A self-develop framework for measuring performance in new enterprises	Performance Based Costing (PBC)
8	Yao and Liu (2006)	Integrated framework of EVA, BSC and ABC	Suggest to use various KPIs
9	Ho (2007)	Use simulation to measure ERP based supply chain performance	Total cost
10	Cai *et al.* (2009)	A framework focused on the performance metrics of Plan, Source, Flexibility, Innovativeness and Information (Partly **SCOR)**	KPIs on Total Cost, Sales, Fill rate, Supply chain responsiveness, Information accuracy
11	Hwang *et al.* (2008)	**SCOR** model version 7.0	Reliability, Responsiveness, Flexibility, Cost, Asset
12	McCormack *et al.* (2008)	**SCOR** Model	Fill rate, delivery
13	Thakkar *et al.* (2009)	A comprehensive framework which integrated balanced scorecard and **SCOR**	Cost, time, capacity, productivity, effectiveness, reliability, and flexibility

The framework in this research was developed based on the SCOR model (Table 2.3). The performance measurement criteria from the SCOR model were divided into effectiveness-related (customer-facing) measures and efficiency-related (internal-facing) measures to evaluate the agility and leanness of supply chains separately (Table 3.4) (Lai *et al.*, 2002). Supply chain Reliability, Responsiveness and Flexibility are the three criteria used to measure the agility of a supply chain:

- Reliability aims to measure the performance for delivering the right product to the right customer at the right time with the right quality;
- Responsiveness focuses on measuring the speed of providing the product to customers ;
- Flexibility measures the ability to handle changes such as demand variation and supply chain disruption.

Costs and Assets measured the operational costs and finance to identify the leanness of the supply chain (Camerinelli, 2005).

Table 3.4: SCOR Model (Source: Adapted from Camerinelli, 2005)

	Performance Measurement Perspectives	**Key Performance Measures (KPIs)**
Efficiency-related (Internal-facing/Leanness)	Costs	Supply chain costs (inventory, operational, transportation, etc)
	Assets	Measures of fixed and working capital; Cash to cash cycle time
Effectiveness-related (Customer-facing/Agility)	Reliability	Perfect order fulfilment; order fulfilment performance; service level
	Responsiveness	Order fulfilment cycle time
	Flexibility	Production flexibility

The author also investigated the performance measures affected by visibility as Key Performance Indicators (KPIs) to monitor supply chain performance. The major KPIs of the framework were the bullwhip effect (Chen *et al.*, 2000; Yu *et al.*, 2001), the service level (Bourland *et al.*, 1996; Zhao *et al.*, 2002; Gunasekaran *et al.*, 2004; McCormack *et al.*, 2008), the inventory level (Cachon and Fisher, 2000; Chen *et al.*, 2000; Li *et al.*, 2001; Yu *et al.*, 2001), the order fill rate (Li *et al.*, 2001; McCormack *et al.*, 2008; Cai *et al.*, 2009), the backorder penalty cost (Cachon and Fisher, 2000), the inventory costs (Chen *et al.*, 2000; Li *et al.*, 2001; Lee, 2004), and the total costs (Zhao *et al.*, 2002; Gunasekaran *et al.*, 2004; Cai *et al.*, 2009).

The performance measurement framework adopted in this research is illustrated in Table 3.5. Apart from the discussed KPIs, other KPIs related to flexibility and the bullwhip effects were chosen to measure to what extent the information visibility impacted on supply chain performance. Furthermore, a quantitative trust measurement was designed to measure the trust building among the supply chain partners with the increased visibility levels. The equations for the performance measures are presented in chapter four.

Table 3.5: The performance measurement framework

	Performance Measurement Perspectives	**Performance Measures (KPIs)**	**Formula**
Resource (Leanness)	Costs	Cost of Inventory (Raw Material & Finished Goods)	RM Cost + FG Cost
		Operation Cost	Manufacturing Cost + Delivery Cost + Fix Cost
		Penalty Cost	Backorders
		Total Cost	Cost of Inventory + Operation Cost+ Penalty Cost
	Asset Management	Inventory Turnover	Cost of Goods Sold/Average Inventory
		Overproduction	Finished Goods Before Delivery – Real Demand
		Profitability	Sale – Total Costs
Service Level (Agility)	Supply Chain Reliability	Sale	Sum of items delivered
		Order Fill Rate	Sum of items delivered / Real Demand
	Flexibility	Backorders	Total backorders of the supply chain
		Supply Chain Disruption	Total number of supply chain disruption
Bullwhip Effect	The bullwhip effect	Amplification Ratio	Variance of Finished Goods' Inventory / Variance of demand
		Forecast Accuracy	The Error of Real Demand and Forecast / Real Demand

3.2 Discussion and evaluation

The performance from the simulation is measured using the performance measurement framework. Measures related to the bullwhip effect, leanness, agility and LeAgility are discussed in chapter five. A general discussion to demonstrate the correlation between increased visibility level and improved LeAgility is presented in chapter six. Human issues such as participant behaviours and trust building are also discussed. In addition, the concept of the supply chain visibility solution used in the simulation was assessed through two cases in order to highlight the business implications. One is the West Midlands Collaborative Commerce Marketplace (WMCCM, www.wmccm.co.uk): where the concept of visibility has been implemented as a visibility module to monitor and trace supply chain activities; another is the EU framework seven, Factory of the Future project IMAGINE (http://www.imagine-futurefactory.eu): a visibility solution is the cornerstone of the project to achieve the end-to-end management of dynamic manufacturing networks.

3.3 Summary

A hybrid simulation was adopted to generate primary data to investigate the impact of visibility on improving LeAgile supply chain performance. The results were analysed through a performance measurement framework based on the Supply Chain Operations Reference (SCOR) model. The next chapter describes the simulation design and the performance measurement framework used in the simulation.

4

Simulation Design

The detailed simulation design is introduced in this chapter. The supply chain used in this simulation was modified from a well-documented case study and its parameters and variables were defined in order to re-establish a volatile business environment. A Google based communication and coordination support system was developed based on the hub-and-spoke information sharing architecture to support the participants' decision-making. The scenarios of three experiments were designed to address the research question. The three experiments are Experiment One (Demand Visibility), Experiment Two (Operational Visibility) and Experiment Three (Decoupling Point and Postponement).

4.1 Supply chain structure of simulation

The supply chain used in simulation was chosen from a well-documented case study of Hewlett Packard (HP) Deskjet print supply chain (Kopczak and Lee, 2001). The modified four-echelon supply chain used for this research is shown in Figure 4.1. The modified supply chain targeted two product markets (Products A and B) in two geographical areas (EU and US). Products A and B were produced in a single production line. For example, two components for product A were assembled as Product AE and AU by Participant 4 (Final Assembly and Test, FAT) to target the EU and US markets; after shifting the production line, Product BE and BU could then be assembled. Thus, the complexity of the simulation was believed to be sufficient to represent the business environment of the HP case study, and to evaluate the impact of visibility on supply chain performance.

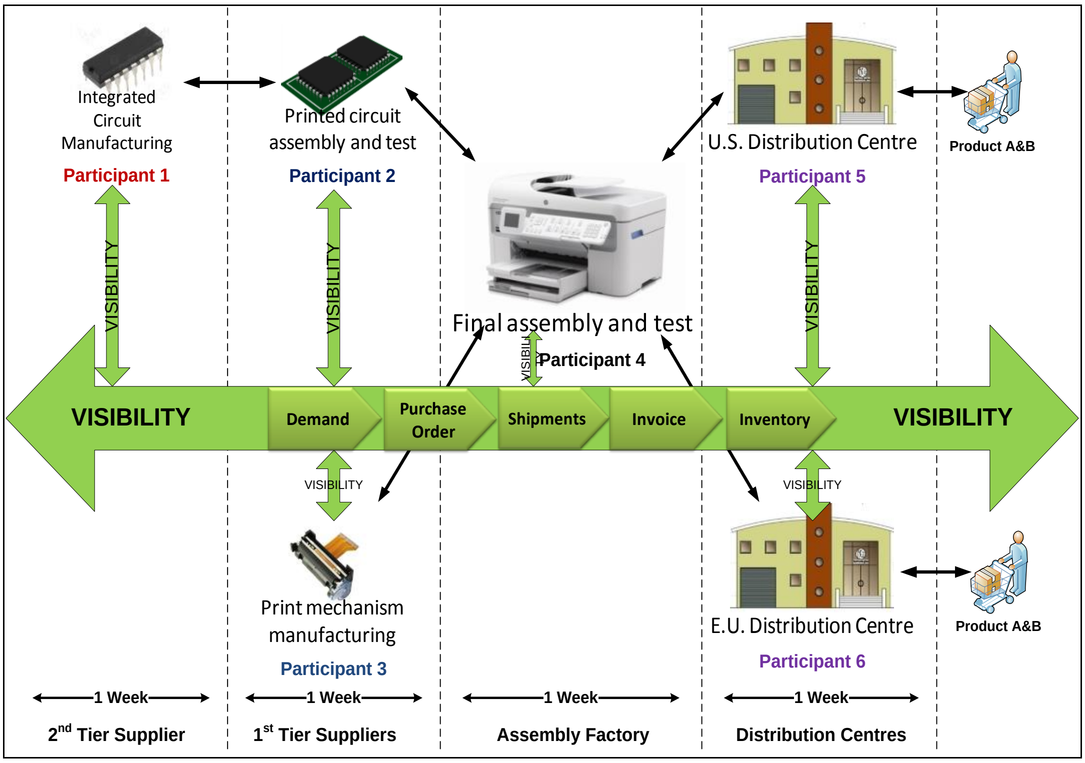


Figure 4.1: The modified supply chain from HP case study

4.2 Simulation parameters and variables

The simplified supply chain may reduce the benefits of visibility; however, the complexity of the supply chain can be simulated by controlling the simulation parameters and variables. In order to examine the capacity of visibility in a fast changing business environment, the parameters and variables were designed in seven aspects: demand pattern, lead time, capacity, forecasting method, inventory management, unexpected events' generation, costs' management.

4.2.1 Demand Pattern

The customer demand was generated based on the demand pattern of the history of sales data of the HP case study. Individual orders were generated randomly within the overall demand pattern in order to examine how well the supply chain responded to a fast changing environment. Appendix 1 lists the details of demand data for Products AE, BE, AU and BU used in the simulation. The simulation used the same demand data for all experiments in order to compare the results from different scenarios. The participants changed their roles in each scenario to reduce the possible impact of memorising the demand data and thus minimising the impact of the 'learning effect' on the supply chain performance.

4.2.2 The lead time of supply chain

As shown in Figure 4.1, the simulation used a fixed one week lead time for all supply chain partners to deliver their orders. The delivery was received by the partners or customers in the following week. As a result, the total cycle time for delivering a printer was four weeks.

4.2.3 Capacity

Manufacturing capicity for each participant was 10,000 units per day (70,000 units per full week). This capacity was sufficient for all participants to cope with the peak demand in one week. The peak of real customer demand was 49,000 for product A and 13,000 units for product B. However, manufacturing capacity in this simulation was still very vulnerable due to the demand fluctuation.

4.2.4 Forecasting

There were two types of forecast used in the simulation. One was a centralised forecast which was generated based on the customer demand by distribution centres (Participants 5 and 6); the other was the forecasts generated by their upstream (direct) customers. Since a good supply chain performance depends on an accurate forecast, all the forecasts were required to update each week in response to new demand data. In the simulation the participants had to change their role for each scenario, so the centralised forecasts generated by distribution centres were changeable. A slight difference in forecast may greatly influence the final supply chain performance. In order to investigate the impact of visibility on supply chain performance, the forecast accuracy had to be maintained at a reasonable level. Therefore, the participants adopted the same forecasting method (Moving Average) in the simulation (see Appendix 2). In this way, the result from each scenario can be used to compare the impact of visibility on the supply chain performance.

4.2.5 Inventory management

There is no specific inventory management philosophy adopted in the simulation. The goal of the inventory management is to hold as little inventory as possible whilst satisfying customer orders. In the simulation, some of the participants used zero inventory management; some of them held a certain level of safety stocks. This reflects the choices made by individual unit managers in a supply chain.

4.2.6 Unexpected events

The simulation used three variables to simulate supply chain uncertainties. They were defect rate, late delivery and machine breakdown which corresponded to the three types of supply chain uncertainty defined by Gaonkar and Viswanadham (2007): Deviation, Disruption and Disaster. The unexpected events were generated randomly in the first scenario and fixed for the rest of the scenarios. Appendix 3 records all the unexpected events of Experiment Two (Operational Visibility) and Three (Decoupling Point and Postponement).

4.2.6.1 Defect rate

Defective products impeded all the participants in Experiment Two and Three. The defect rate for each supply chain partner was generated randomly and the average defect rate was about 1%. In the simulation, participants had to spend a maximum of one day to adjust machines if their defect rates were higher than 1%.

4.2.6.2 Late delivery

Late delivery affected all the supply chain partners in the simulation. There were a total of five late delivery events in the simulation, and they were generated randomly. Once a late delivery happened, the participant was not able to fix it until they received an alert. Then they could choose a solution to cope with the effect of the late delivery of either 1) waiting, or 2) ordering from an alternative supplier at a higher cost. Participants 5 and 6 did not have alternative suppliers since the product they received is the final product in Experiments One and Two.

4.2.6.3 Machine breakdown

As in late delivery, machine breakdown was also generated randomly. However there were only two machine breakdowns for each scenario. Once the machine breakdown had happened, the participant could not produce for the whole week unless they chose one or more of following solutions:

- Solution 1: Using the old machine: at only 20% of the original capacity (2,000 units per day)

- Solution 2: Hiring machines: the same capacity with an extra cost of £5000 per day
- Solution 3: Repairing the machines: taking up to 3 days, at a cost of £4000 per day

4.2.7 Cost Management

There were five types of costs in the simulation, shown in Table 4.1: fixed cost, operation cost, inventory cost, extra cost and penalty cost. A weekly report was provided to all participants at the end of each week in order to help them better understand their financial status and adjust their strategies for the next round. Appendix 4 depicts an example of the calculation for Participant 3's total cost.

Table 4.1: Five types of cost in the simulation

Cost	Description	Formula
Fixed Cost	The fixed cost for each week was £5000	£5000
	The machine setup cost for each production line shift was £500	£500 ×n
Inventory Cost	Raw materials and finished goods	5% of RM stock + 5% of FG stock
Operation Cost	Manufacturing Cost	10% of scheduled production
	Delivery Cost	5% of Production delivery
Penalty cost	Penalty Cost	£1 ×backorders
Extra cost	Machine Breakdown	S1+S2+S3
	Late Delivery	50% of the order from the market

4.3 Information sharing method

The simulations used the same hub-and-spoke information sharing method for all scenarios. Ryu *et al.* (2009) developed two information sharing methods based on this structure: Planned Demand Transferring Method (PDTM) and Forecasted Demand Distributing Method (FDDM).

4.3.1 Planned Demand Transferring Method (PDTM)

The forecast of PDTM is generated by the partners close to the customer demand and passed to the rest of the partners sequentially (see Figure 4.2-a). In this way, the inventory between two partners can be controlled at a low level, since their production scheduling is made based on the forecast of their direct customers. However, the accuracy of this method can worsen sharply, as each partner needs time to make their own plan and to transfer the new forecast based on their plan; this can lead to the serious bullwhip effect.

4.3.2 Forecasted Demand Distributing Method (FDDM)

In this method, the forecast is made by a third-party organisation and then passed to each partner (Figure 4.2-b). It considers each partner's lead time and inventory level, and then makes the forecast for each one. Ryu *et al.* (2009) believed that this method gives the supply chain a smooth and low inventory, and high accuracy of forecast. But unlike the PDTM, the adjacent partners make their production plan based on the forecast provided by the third-party organisation instead of their direct customers, so the service level between them should be worse than with PDTM.

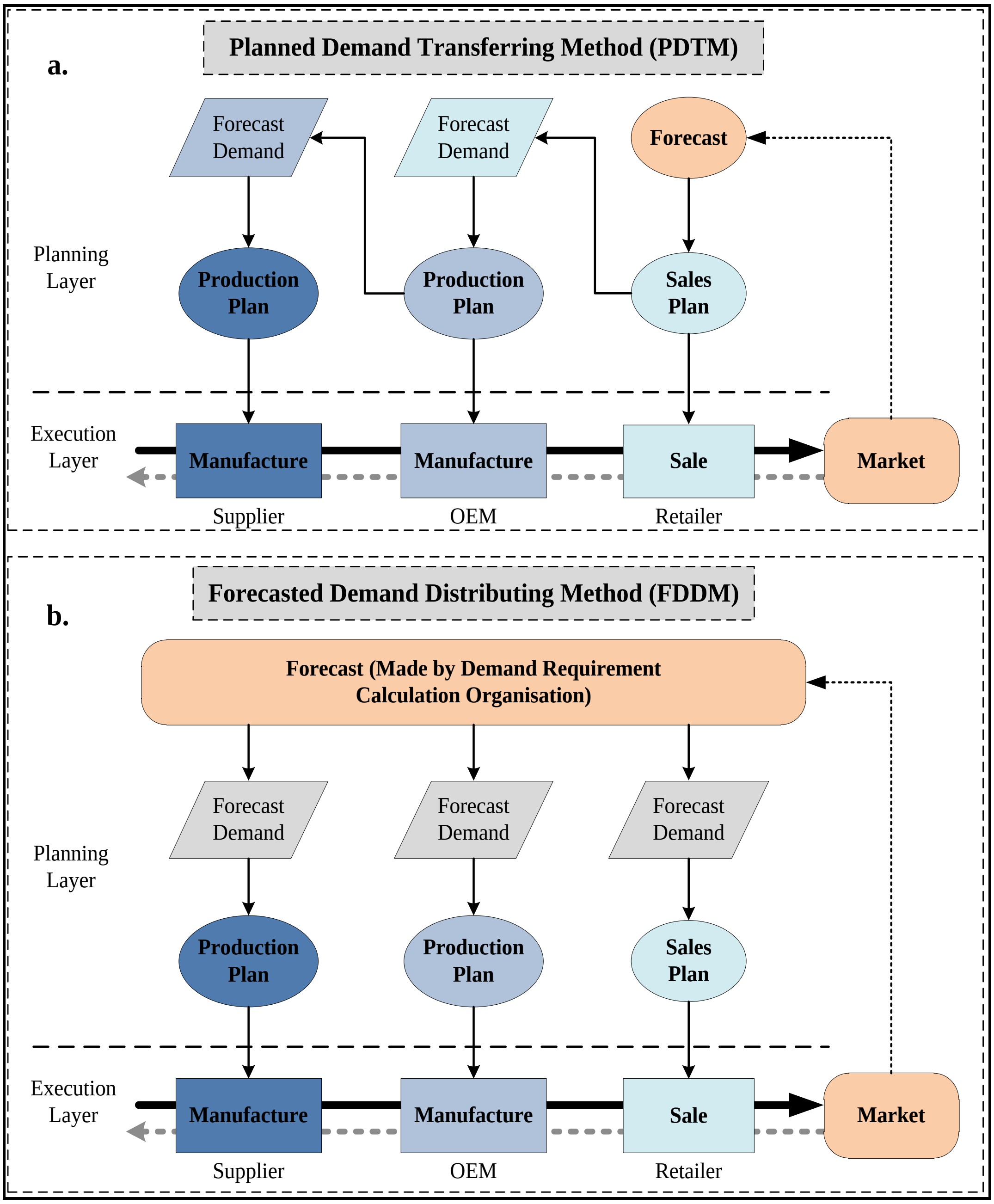


Figure 4.2: Information flow of PDMT and DDDM (Source: Adapted from Ryu et al., 2009)

4.3.3 The information sharing method for the simulation

In order to examine the impact of the visibility, the author developed a new information sharing method which attempts to combine the benefits of both PDMT and DDDM. The actual information sharing method used in these simulations is illustrated in Figure 4.3. There are two types of forecast in supply chains: centralised forecast and forecast from direct customers. In this research, the centralised forecast was generated by the distribution centres (Participants 5 and 6) since they were closest to the end customers. Each supply chain partner could then make their production plan based on the two forecasts in order to better balance their inventory level and service level. Through doing so, the impact of increased visibility on supply chain partners' behaviours could be analysed by tracking their decision choices.

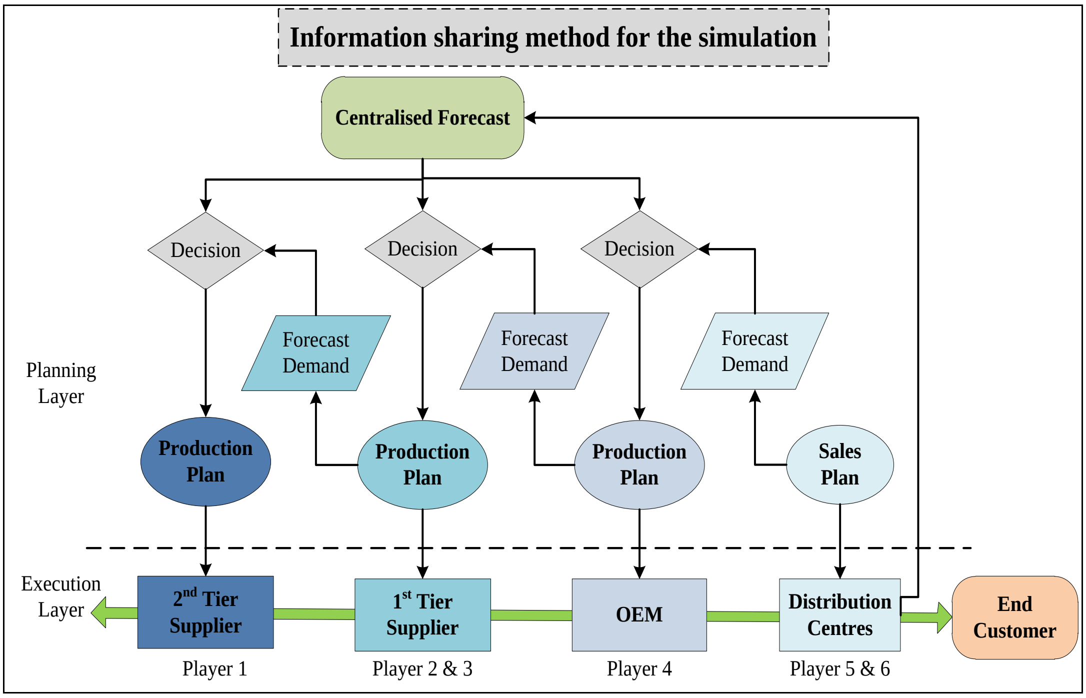


Figure 4.3: The information sharing method for the simulation

4.4 The simulation tool

A selection of Google products (Google Docs, Google Wave and Google Sites) were chosen to enable a visibility system utilising the chosen information sharing method. The system automatically recorded inventory data, manufacturing data, order and sale into a central database. The participants were allowed to access different information on their dashboard according to the scenario configuration. A project workspace was created on a Google Sites (www.scvforbusiness.com) to help the participants manage their processes.

4.4.1 Data input portal and central database

The data flow amongst the data entry portals, central database and the participants is illustrated in Figure 4.4. The central database recorded all the data, and then pushed the relevant data to each individual participant and the shared portal according to the information sharing configuration and defined KPIs. The participant could then view their supply chain status on their dashboard at any time. In the simulation, the recorded data were generated by the following formula:

$$Output = f_M(x)\left(1 - f_D(x)\right)$$

$$where \quad f_M(x) \geq f_{In}(x) = f_{Order}(x) + f_{In}(x-1)$$

$$f_M: Manufacturing\ data$$
$$f_{In}: Inventory$$
$$f_{order}: Order$$
$$f_D: Defect\ Rate$$

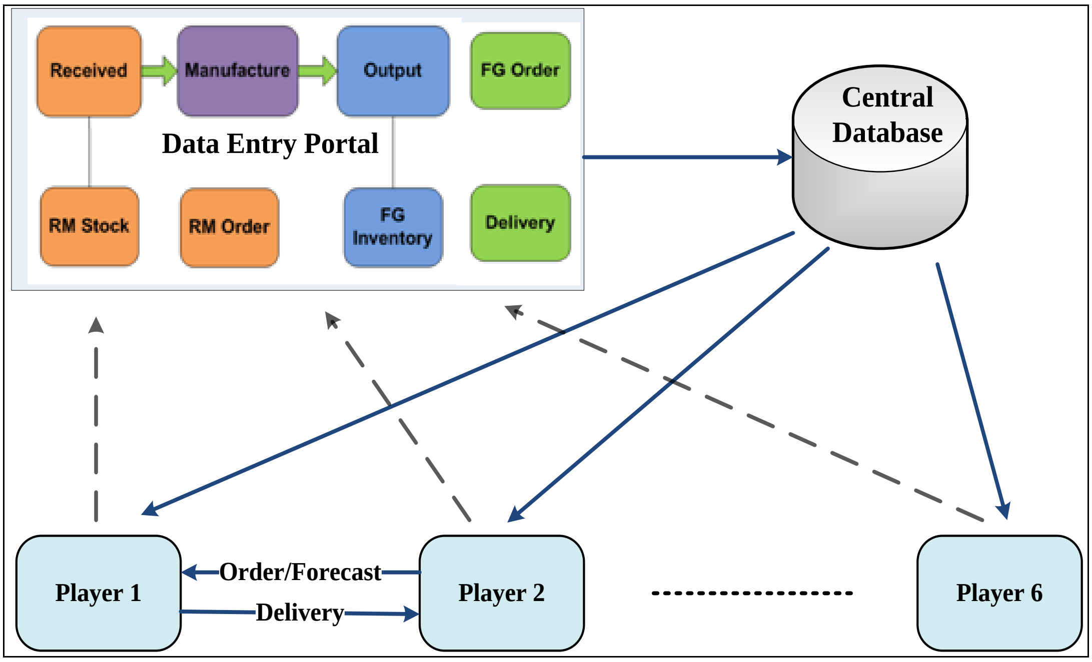


Figure 4.4: The data flow of the simulation

4.4.2 Dashboard

The dashboard showed the supply chain status for four areas: inventory level, service level, shared information, and unexpected events. The participants could define KPIs limits for these areas and monitor them by red (urgent), amber (attention), and green colours (fine) coding. Taking inventory management as an example, red indicated the inventory was above the highest acceptable stock level or below the lowest acceptable stock level, and an alert would be sent to remind participants to take immediate action. Amber meant attention was required and green showed the inventory to be within an agreed level. Figure 5.5 shows the dashboard for Participant 3 in week 7.

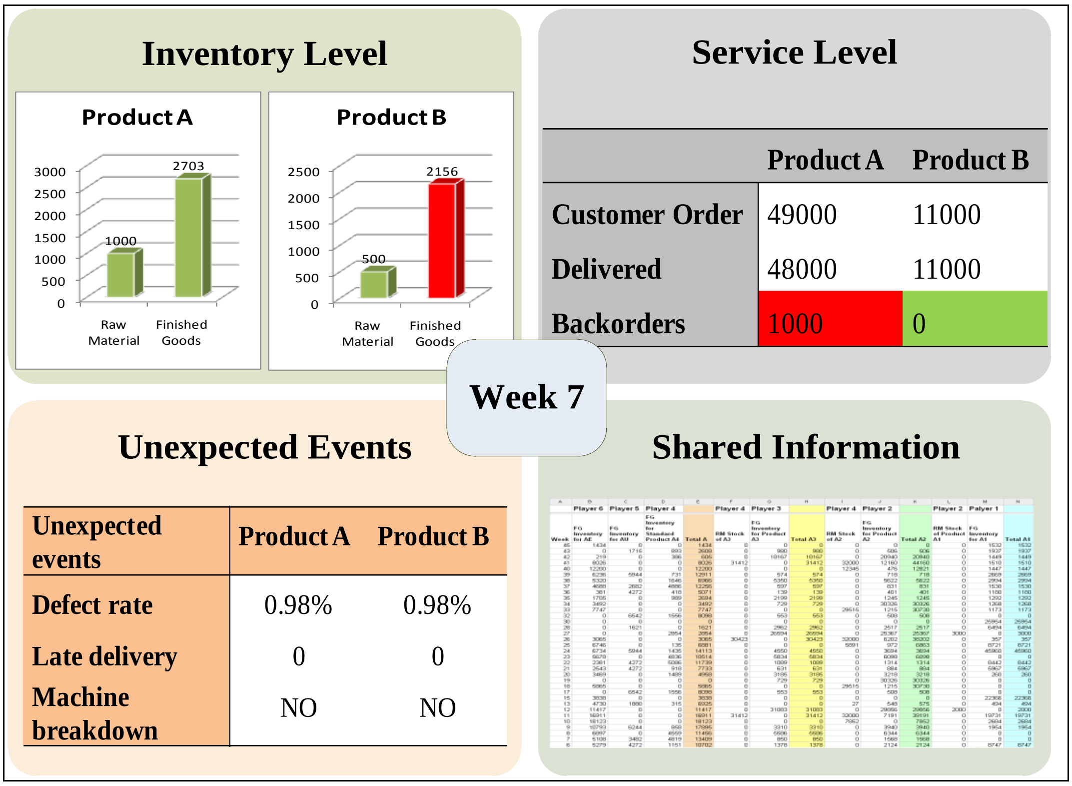


Figure 4.5: A dashboard example

4.5 Three experiments and their scenarios

With respect to visibility, three experiments were selected as follows:

1. Demand Visibility experiment – seeing what is required

   To investigate the effect of increased visibility on customer demand on improving supply chain LeAgility

2. Operational Visibility experiment – seeing what is the current situation

   To examine the impact of increased operational visibility on improving supply chain LeAgility

3. Decoupling Point & Postponement experiment

   To identify the advantage of supply chain visibility approach over the decoupling point and postponement approaches for creating a LeAgile supply chain.

Each experiment included five scenarios, and each scenario represented one specific visibility level. There were sixteen rounds in each scenario and the supply chain needed the first four rounds to load the chain. The scenario configurations considered of two variables: shared information (Table 2.3) and the information sharing frequency (heartbeat). The visibility level increases with sharing more information and/or higher frequency.

4.5.1 Experiment One - Demand Visibility experiment

The Demand Visibility experiment was designed to examine the supply chain performance after seeing what was required by the customer. The simulation focused on sharing demand information in a planned business environment by excluding the operational information. This scenario assessed supply chain performance against increasing levels of information sharing. Table 4.2 shows the five scenarios used in this experiment.

Table 4.2: Scenarios for Experiment One - Demand visibility experiment

	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5
Forecast		√	√	√	√
Capacity		√			
Production schedule		√	√	√	√
Inventory			√	√	√
Order/Real demand				√	√
Heartbeat	1 week	1 week	1 week	1 week	2 weeks

The visibility levels in this experiment were defined by the increased levels of information sharing (Table 2.3). Scenario 1.1 was designed as a no visibility scenario with limited information sharing. Scenario 1.2 aimed to simulate the supply chain performance against the shared forecast related information, such as forecast, capacity, and production schedule. In Scenario 1.3, with the relationship developed, the inventory information was shared in the supply chain; such information included the raw material inventory, work in process and the finished goods stock. Scenario 1.4 was designed to examine the effect of sharing the real customer demand on the supply chain performance. Scenario 1.5 reduced the information sharing frequency to every two weeks. It was designed to explore the impact of information sharing frequency on supply chain performance.

4.5.2 Experiment Two - Operational Visibility experiment

The Operational Visibility experiment was designed to explore the effect of granting access to the current operational status of each partner, to the other partners. With increased visibility, supply chain managers should then respond to changing situations with more accuracy and confidence. The three common types of unplanned events were replicated: an increased defect rate, late delivery, and machine breakdown. Table 4.3 illustrates the different aspects of visibility enabled in Experiment Two.

Table 4.3: Scenarios for Experiment Two - Operational Visibility experiment

	Scenario 2.1	Scenario 2.2	Scenario 2.3	Scenario 2.4	Scenario 2.5
Forecast	√	√	√	√	√
Capacity	√	√	√	√	√
Production schedule	√	√	√	√	√
Inventory		√	√	√	√
Order/Real demand			√	√	√
Operational information					
Order status				√	√
Delivery status				√	√
Operational status				√	√
Heartbeat	1 week	1 week	1 week	1 week	2 weeks

4.5.3 Experiment Three - Decoupling Point & Postponement experiment

In this experiment, the supply chain visibility approach was compared to the decoupling point and late customisation approaches in order to identify the advantages of the supply chain visibility approach for establishing a LeAgile supply chain. In the original HP case study, the authors (Kopczak and Lee, 2001) suggested solving the supply chain issues for HP by adopting the decoupling points and postponement methods. In Experiment Three, two material decoupling points and one information decoupling point were integrated (Figure 4.6) into the simulation supply chain. The information decoupling point was enabled from the second tier supplier and material decoupling points were placed between the Assembly factory and Distribution centres.

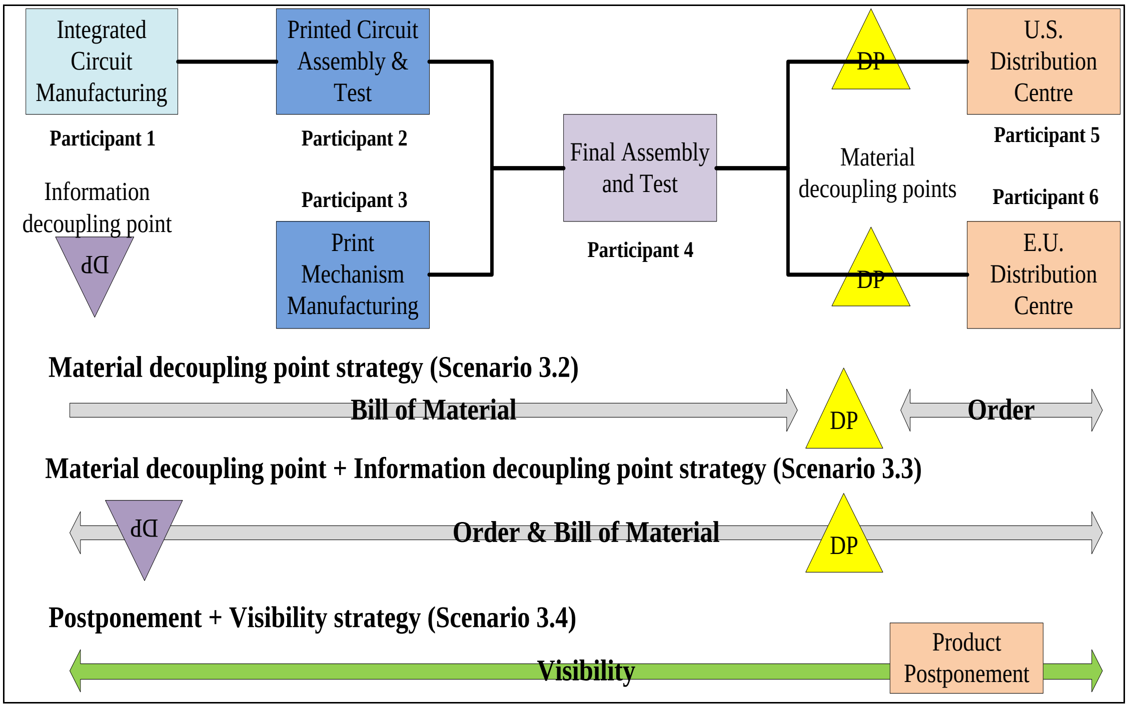


Figure 4.6: the modified supply chain structure in Experiment Three

The detailed scenario configurations for Experiment Three are shown in Table 4.4. Information in this experiment was shared with the same frequency in order to compare the supply chain LeAgility for different strategies. In Scenario 3.1, an information decoupling point was placed in the 2nd tier suppliers (Figure 4.6) to examine its impact on supply chain performance. In Scenario 3.2, two material decoupling points were placed between the Assembly factory and Distribution centres (Figure 4.6). The suppliers produced the standardised components and customised in distribution centres. Scenario 3.3 adopted both the information and material decoupling points. Scenario 3.4 was designed to explore the impact of implementing the visibility approach in the postponement supply chain (Figure 4.6). It produced the standardised products and customised in the final stage. Scenario 3.5 implemented the visibility approach in the original supply chain.

Table 4.4: scenarios for Experiment Three - Decoupling Point & Postponement experiment

	Strategy	Supply chain type	Forecast	Inventory	Real demand	Unexpected event
Scenario 3.1	Information decoupling point	Original	√	√	×	×
Scenario 3.2	Material decoupling point	Standard Product + Postponement	√	√	×	×
Scenario 3.3	Information decoupling + Material decoupling	Standard Product + Postponement	√	√	√	×
Scenario 3.4	Postponement + Visibility	Standard Product + Postponement	√	√	√	√
Scenario 3.5	Visibility	Original	√	√	√	√

4.6 Performance measurement framework

Quantitative and qualitative research methods were both used to measure the performance of the selected supply chain. The results from the simulation were measured quantitatively by the performance measurement framework developed in Chapter 3 (Table 3.4). It measured the supply chain LeAgility for each scenario in three separate areas: the bullwhip effect, leanness, and agility. A trust analyse was carried out quantitatively and qualitatively by separately measuring the trust indicator and observation of the participant behaviours during the decision making. A supply chain total value measurement and a synthesis graph measurement were used to show the overall supply chain performance both quantitatively and graphically.

4.6.1 Bullwhip effect measurement

The 'bullwhip effect', also known as the 'Forester effect' or 'demand amplification', is defined as "*the amplification of demand variability from a downstream site to an upstream site*" (Cachon *et al.*, 2007). It is an observed phenomenon especially in forecast-driven supply chains. It is well established in literature that the bullwhip effect can be measured per echelon by calculating its amplification ratio (Fransoo and Wouters, 1997). In addition, forecast error, as one of the main sources of the causes of the bullwhip effect, is measured by calculating the forecast accuracy.

4.6.1.1 Amplification ratio

The amplification ratio measures the demand amplification of each echelon of the supply chain. In the research simulation, it can be calculated by using the variance of finished goods ($f_{FG}(x)$) divided by variance of real demand ($f_{RD}(y)$) (Equation 1). A smaller ratio indicates better bullwhip effect mitigation. By comparing the amplification ratio of the scenarios, the best scenario for mitigating the bullwhip effect can be identified.

$$Amplification\ Ratio = \frac{\boldsymbol{\sigma}^2_{\text{FG inventory}}}{\boldsymbol{\sigma}^2_{\text{Real Demand}}} = \frac{\sum_1^n (f_{FG}(\mathrm{x}) - \overline{f_{FG}})^2/\mathrm{N}}{\sum_1^n (f_{RD}(\mathrm{y}) - \overline{f_{RD}})^2/\mathrm{N}} \quad (1)$$

4.6.1.2 Forecast accuracy

The forecast accuracy measures how accurate each participant's forecast is, compared to real demand. It calculates the error between each player's forecast ($f(x)$) and the real customer demand ($f_{RD}(y)$) in each week, then shows the forecast accuracy as the average of the error to the real demand. A lower number suggests better performance.

$$forecast\ accuracy = \frac{\sum_{1}^{n} Z_{error}}{N} \tag{2}$$

$$where \qquad Z_{error} = \frac{|f(x) - f_{RD}(y)|}{f_{RD}(y)}$$

4.6.2 Trust analysis

Trust in a supply chain can be defined in many different ways. From its generic meaning, it means a willingness of a company to take a risk or expose itself in relation to another (Sahay, 2003). In this experiment, trust means a willingness to follow the direct customer or central information. Therefore, measuring trust between supply chain partners means measuring the difference between the participants' purchasing behaviour with the centralised forecast or their direct customers' forecasts. A trust indicator was used to indicate the distance between their purchasing ($f_{Order}(x)$) and the centralised forecast ($f_{CF}(y)$), or the forecast from direct customers ($f_{DCF}(y)$) (Equation (3)). The lower the value of the trust indicator, the stronger the trust.

$$Trust\ Indicator = \sqrt{\frac{\sum_1^n (f_{Order}(x) - f_{CF}(y))^2}{N}}$$

$$or \qquad \sqrt{\frac{\sum_1^n (f_{Order}(x) - f_{DCF}(y))^2}{N}} \qquad (3)$$

4.6.3 Leanness measurement

The leanness of the supply chain was measured for three perspectives: costs, inventory, and overproduction.

4.6.3.1 Cost Measurement

The total cost in the simulation was the sum of five types of cost: fixed cost, inventory cost, operation cost, penalty cost, and extra cost (see Table 4.1). A smaller value indicates better cost reduction.

4.6.3.2 Overproduction measurement

Overproduction indicates the total excess production over the real demand in each scenario. A small number for overproduction means the supply chain has better material and information flow, and fewer inventories.

4.6.3.3 Inventory measurement

The inventories in this simulation included the raw material inventory and the finished goods inventory. A smaller value indicates better inventory control.

4.6.4 Agility measurement

The supply chain agility was measured by customer service level and flexibility.

4.6.4.1 Customer service level

The customer service level measures the order fill rate of end customers. In the simulation, it was calculated by the percentage of sales divided by real demand (Equation 4). A higher percentage indicates a better customer service level.

$$Customer\ Service\ Level = \frac{Sales}{Real\ Demand} \times 100\% \tag{4}$$

4.6.4.2 Flexibility

An agile supply chain is flexible in order to cope with changes. In this simulation, dealing with changes was viewed as dealing with supply chain disruptions. Therefore, the flexibility of the supply chain was measured by analysing backorders and the number of disruptions. The disruptions in this simulation are defined as unplanned production stoppages caused by unexpected events occurrence and raw material shortages. The smaller the number of backorder and disruption, the more flexible the supply chain was.

4.6.5 The overall supply chain performance

The overall supply chain performance was measured through the total value of the supply chain and a synthesis graph analysis using both a quantitative method and graphical method.

4.6.5.1 Supply chain total value

A total value for a supply chain was suggested by Johansson *et al.* (1993) to explain the rationale behind the adoption of either paradigms (lean or agile) in terms of cost or service. The paradigms can be linked to Equation (5) (Johansson *et al.*, 1993), which was calculated for four dimensions: quality, service level, costs, and lead time. The value resulting from the equation describes the total performance in terms of value to the customer (Mason-Jones *et al.*, 2000a). The higher the value, the better the overall supply chain performance is. This equation was also adopted to analyse the performance of each individual actor in the chain, to show individual performance variations against overall performance.

$$Total\ Value = \frac{Quality\ \times Service\ Level}{Costs\ \times Lead\ Time} \tag{5}$$

4.6.5.2 Synthesis graph analysis

The supply chain total value shows to what extent supply chain LeAgility has improved in terms of quality, service level, costs, and lead time. However, it cannot provide such information as flexibility, profitability, and forecast accuracy. Therefore, a synthesis graph analysis was created to compare the supply chain performance for different scenarios. It shows the results of each measure of the performance measurement framework (Table 3.6) in a visual graph, according to their ranking. Figure 4.7 illustrates an example of the synthesis graph for Experiment One. It ranks the performance of the five scenarios on each measure for Experiment One. A rank of 1 indicates the best performance.

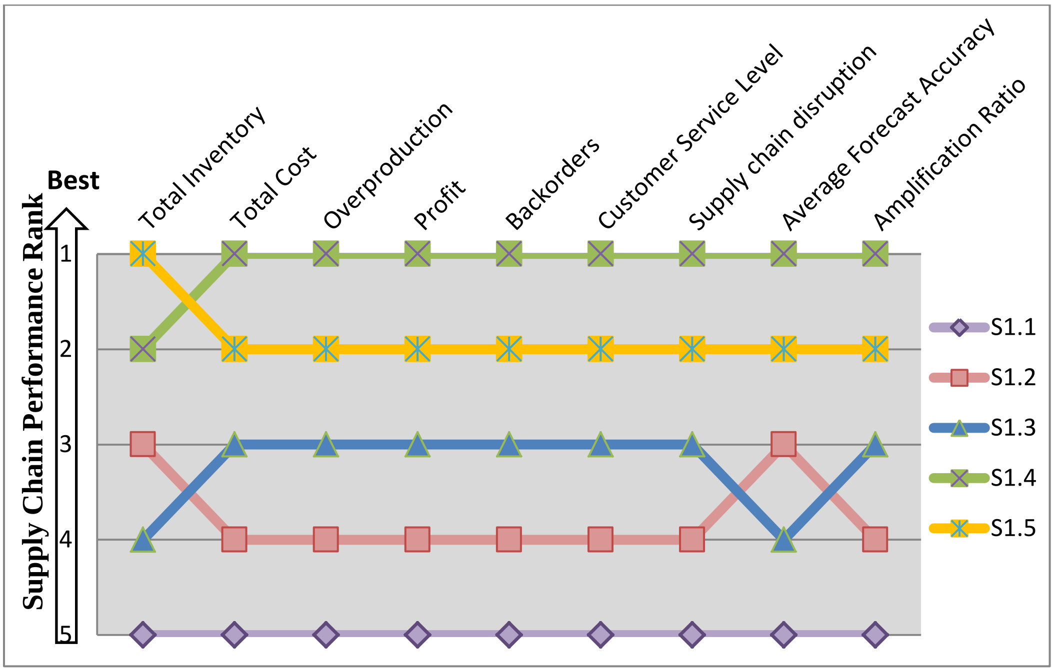


Figure 4.7: An example of synthesis graph analyse for the simulation

4.7 Summary

The simulation used a typical supply chain modified from the HP printer case study. Two types of product needed to be produced in a single production line and customised for two different markets. A Google based cloud system was designed for the simulation, to drive the experiment and collect the data in three experiments with different scenarios. Their LeAgility were measured by a performance measurement framework based on the SCOR model. The next chapter presented an analysis and discussion of the results from the three experiments described.

5

Simulation Results

This chapter analyses the results of the three experiments described in Chapter Four, in order to address the research question: *To what extent can a LeAgile supply chain be achieved through improved supply chain visibility?* Therefore, Experiment One (Demand Visibility) and Experiment Two (Operational Visibility) were designed to investigate the correlation between a LeAgile supply chain and the degree of supply chain visibility in the supply chain, Experiment Three (Decoupling Point and Postponement) was designed to identify the advantages of the supply chain visibility approach over the other approaches for creating a LeAgile supply chain.

5.1 Visibility and bullwhip effect

An objective of this research was to investigate the effect of visibility on the bullwhip effect, (also known as the Forrester effect) which is a common phenomenon to be addressed in any discussion on supply chain performance. Significant research has been published in this area on understanding its causes and the various solutions to mitigate it. For instance, sharing centralised forecast and orders are recognised as effective solutions to help mitigate its effect (Nienhaus *et al.*, 2006; Kelepouris *et al.*, 2008; Wright and Yuan, 2008; Chen and Lee, 2009); others believe that sharing inventory information from all suppliers could further reduce the bullwhip effect (Yang *et al.*, 2003; Coppinia *et al.*, 2010); however, Ouyang (2007) argues that the bullwhip effect cannot be mitigated without knowing real customer demand. The impact of sharing operational information on reducing the bullwhip effect is rarely studied. The results from Experiment One (Demand Visibility) and Experiment Two (Operational Visibility) suggest that enabling information visibility significantly mitigated the bullwhip effect in the case studies.

Previous research has focused on analysing and identifying the possible causes of the bullwhip effect. These causes can be classified into human behavioural causes and operational causes. Nienhaus et al (2006) studied how the human behaviour amplifies the bullwhip effect and suggested that some aspects in human behaviours, like panic ordering, safe harbour and under estimating the value of information are the main reasons for the bullwhip effect. Other researchers pointed out that neglecting time delays in making ordering decisions

(Croson and Donohue, 2009; Steckel, et al, 2004) and lack of training (Wu and Katok, 2006) are also important for the bullwhip effect reduction. In literature, the majority research focused on identifying the causes of the bullwhip effect in the perspective of operational management. The operational causes for the bullwhip effect can be summarised as demand processing (Lee et al. 1997a, 1997b, Wang et. Al., 2010, Sodhi and Tang, 2011; zhang and burke, 2011), order batching (Lee et al. 1997a, 1997b, Simchi-Levi et al. 2003, Warburton, 2004), price fluctuations (Lee et al. 1997a, 1997b, zhang and burke, 2011), lead time variability (Lee et al. 1997a, 1997b, Simchi-Levi et al. 2003; Heydari et al, 2009; Sodhi and Tang, 2011), Rationing and shortage gaming (Lee et al. 1997a, 1997b), inventory and replenishment policy (Chandra and Grabis, 2005; Aharon et al, 2009; Jakšič and Rusjan, 2008; Su and Wong, 2008), lack of transparency (Lee, et al, 1997a; Sohn and Lim, 2008; Lee et al, 2000; Zhao and Wang, 2008), lack of synchronization (Bayraktar et al, 2008), capacity limits (Alony and Munoz, 2007), company processes (Moyaux et al, 2007), number of echelons (Alony and Munoz, 2007).

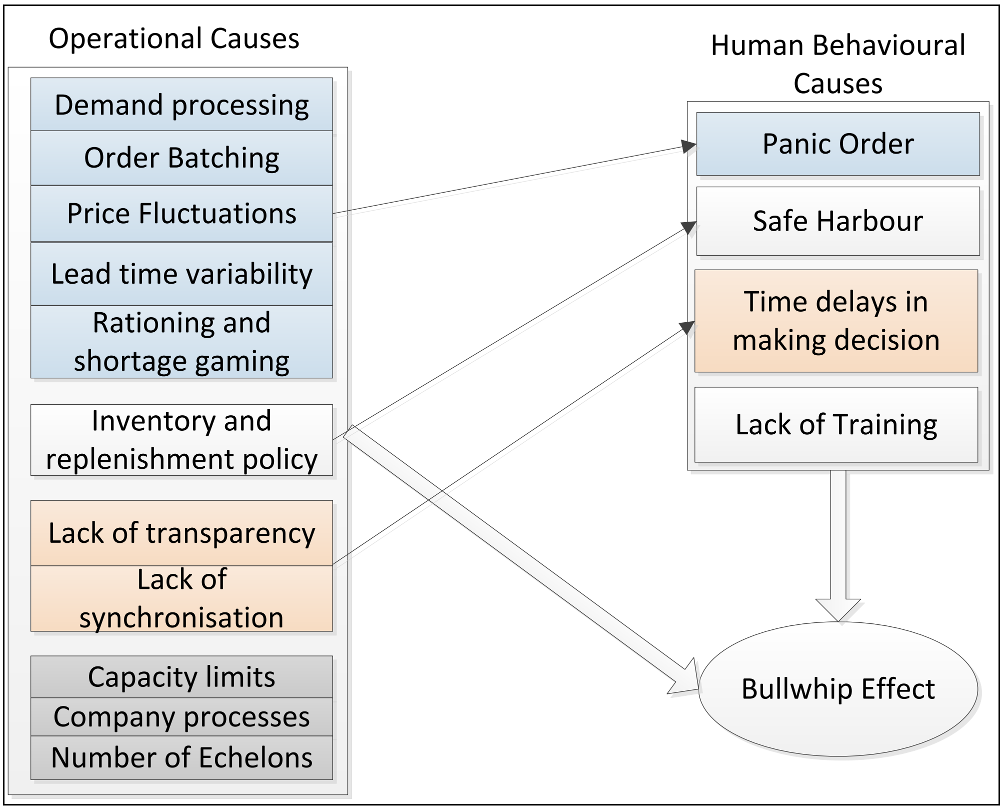


Figure 5.1: Causes of bullwhip effect

A great number of researchers believe the primary cause for the bullwhip effect is the delayed information flow in supply chains, since it takes time to pass the updated information to all relevant suppliers and these suppliers need time to react the change (Lee et al, 1997a, 1997b, Nienhaus et al, 2006; zhang and burke, 2011; Wang et al, 2010). In this research, the author reduces the time delays of information flow and mitigates the bullwhip effect by improving the visibility on demand and operational related information and synchronising the supply chain activities (Figure 5.1).

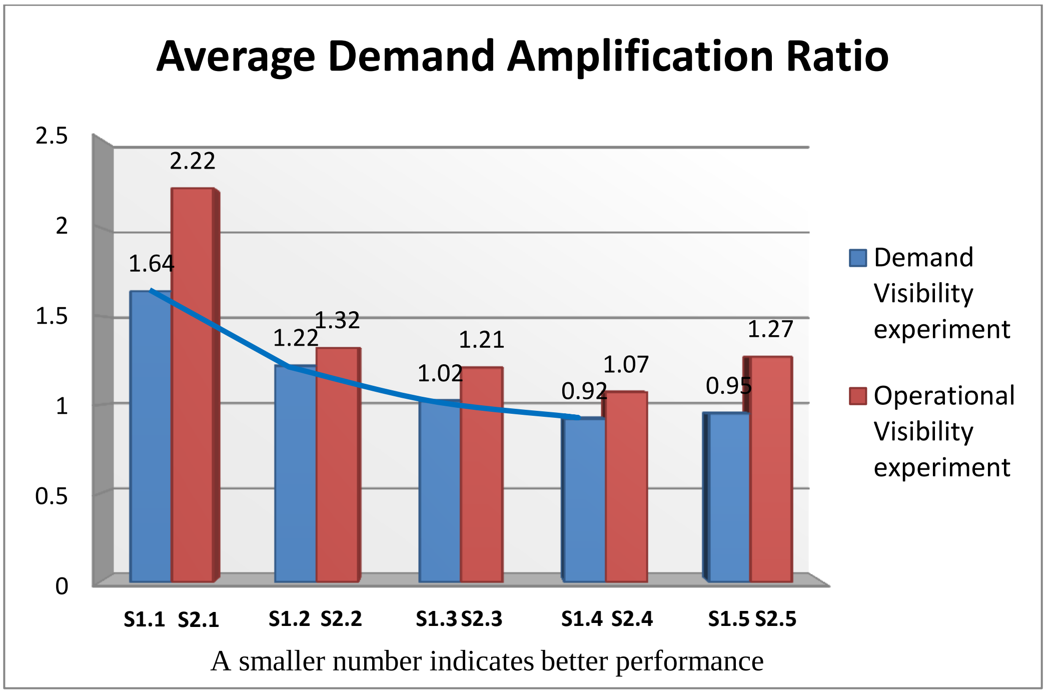


Figure 5.2: The average demand amplification ratio for Demand Visibility and Operational Visibility experiments

The bullwhip effect in this research is measured by the average demand amplification ratio of each scenario (See Chapter 4.6.1). Figure 5.2 shows the average demand amplification ratio for the Demand Visibility and Operational Visibility experiments. The horizontal axis describes the five scenarios for each experiment, and the vertical axis is the value of the demand amplification ratio; a smaller value indicates better performance. Blue represents the Demand Visibility experiment, and red the Operational Visibility experiment. The blue line shows that the bullwhip effect reduces with the increased visibility level in the Demand Visibility experiment. The demand amplification ratio decreases constantly from 1.64 (S1.1) to 0.92 (S1.4) with increased demand visibility. In the Operational Visibility experiment, the demand amplification ratio reduces from 2.22 to 1.21 (S2.3) with the same information shared; however, it further reduces from 1.21 to 1.07 (S2.4) when operational information is shared every week. These results verify the findings of other researchers: the supply chain bullwhip effect is mitigated significantly by sharing forecast (Wright and Yuan, 2008), inventory (Yang *et al.*, 2003) and real customer demand information (Ouyang, 2007); in addition, the results indicate that increased visibility of operational information could further reduce bullwhip effects by 11.6% in the scenarios used. However, the bullwhip effect still exists even when operational information is shared by the supply partners.

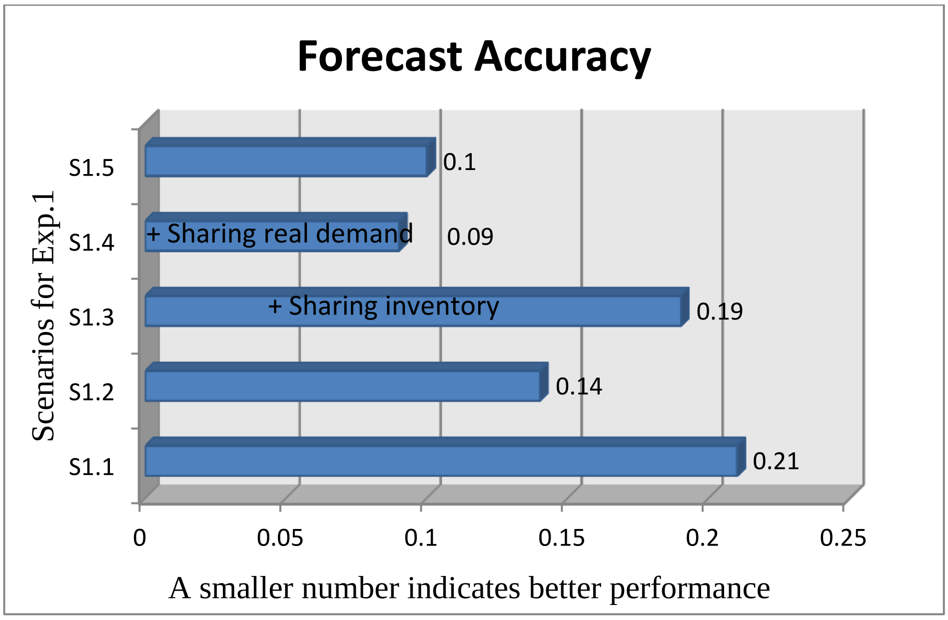


Figure 5.3: the forecast accuracy for Demand Visibility experiment

Increased information visibility also improves the supply partners' forecast accuracy in this simulation. The forecast accuracy of the participants for the Demand Visibility experiment is shown in Figure 5.3. The forecast becomes more accurate after sharing all of the forecast information from the different participants (Scenario 1.2). Research in literature suggests that sharing inventory information in a supply chain by using Electronic Data Interchange (EDI) or Vender-managed Inventory (VIM), is an effective method to forecast and maintain a certain level of inventory (Yang *et al.*, 2003; Yao and Dresner, 2008).

Interestingly, Scenario 1.3 shows poorer forecast accuracy than Scenario 1.2 (S1.2), though more information (inventory) is shared. This may be a result of poor information quality in the experiment. Effective information sharing depends on the elements of timeliness, accuracy, and completeness (Forslund and Jonsson, 2007). In this simulation, inventory and forecast were shared in a timely manner, and accurately, with all supply partners. The suppliers made their production plans based on two types of forecast: the centralised forecast and the forecast from their direct customers. The supply chain partners preferred to follow their direct customers' forecast in the Demand Visibility experiment (trust is probably the reason, see Chapter 6.3). Sharing distribution centres' forecast and inventory information was more valuable to the direct suppliers than further upstream suppliers, since the lead time of the simulation supply chain was four weeks. Direct suppliers could make new forecast based on the spare inventory, and then pass this new forecast to their suppliers. This delayed information could affect the forecast of the upstream suppliers. Without accessing real customer demand as a reference standard, the shared information becomes inaccurate and unreliable, and probably affected the forecast accuracy of the upstream suppliers.

According to Omar *et al.* (2010), the actual customer orders could positively influence the upstream suppliers' production forecast accuracy and inventory efficiency. When the real customer demand is shared in the simulation supply chain, the participants have the most accurate forecast in the experiment.

The participants' individual forecast and centralised forecast for different scenarios from the Demand Visibility experiment are shown in Figure 5.4. The yellow line indicates the centralised forecast, and other colours present the forecast of the different participants. It shows that the participants' forecasts get closer to the centralised forecast from Scenario 1.1 to Scenario 1.4. It seems that sharing customer demand information across the supply chain encouraged the participants to merge their individual forecasts towards a centralised demand driven forecast. The value of the centralized forecast information is recognized only when access to real customer demand data is made available. Actual customer data helps to verify the validity of centralized demand and merge individual forecasts to a centralized demand driven forecast.

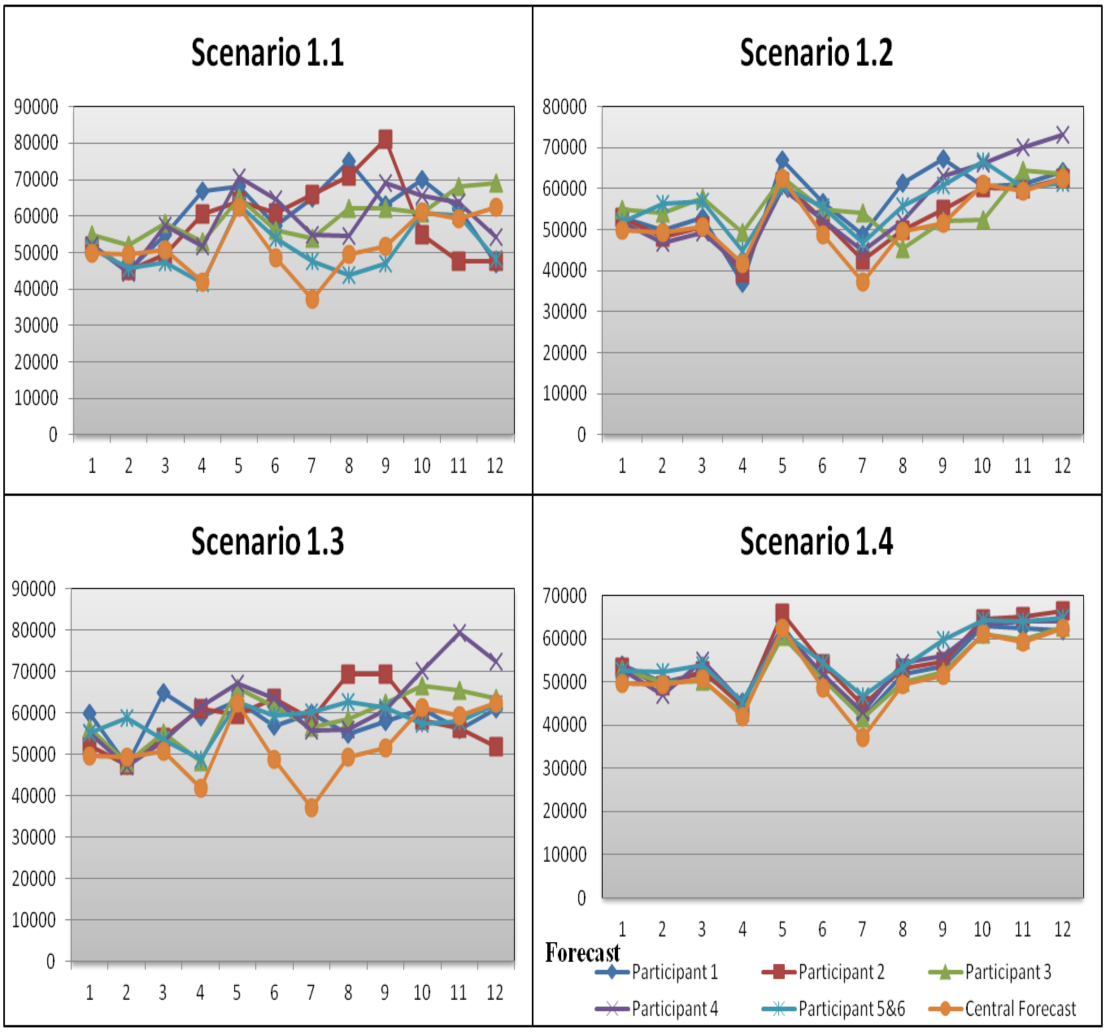


Figure 5.4: Centralized forecast and participants' forecast for Demand Visibility experiment

Published research on the bullwhip effect has focused on identifying its causes in behavioural and operational aspects, and suggesting approaches to mitigating its impact. For instance, the most discussed approach is to provide the centralised demand information to each stage of the supply chain (Nienhaus *et al.*, 2006; Ouyang, 2007; Kelepouris *et al.*, 2008; Wright and Yuan, 2008; Chen and Lee, 2009); and Nienhaus *et al.* (2006) observed that human behaviour (namely "safe harbour" and "panic") had a negative contribution to demand amplification through the online beer game. This research presents a different focus from previous research on the bullwhip effect in three ways.

1. Many studies focused on reducing the bullwhip effect through sharing order, inventory, and demand information in a two-echelon supply chain (Yu *et al.*, 2001; Yang *et al.*, 2003; Kelepouris *et al.*, 2008; Wright and Yuan, 2008; Chen and Lee, 2009). This research investigates the impact of sharing operational information on the mitigation of the bullwhip effect in a four-echelon supply chain.
2. In this research, the main cause of the bullwhip effect is the delayed information flow in the supply chain. Enabling information visibility across the entire supply chain reduces its effect. The results show a 43.9% reduction of demand amplification after sharing inventory and customer demand.
3. The impact of improved visibility of operational information is also investigated in this research. The demand amplification ratio further reduces by 11.6% after sharing operational information.

5.2 Visibility and leanness

'Lean' is a strategy about '*doing more with less'* (Agarwal *et al.*, 2006), and focuses on using less space, less effort, less time, fewer defects and lower volume requirements (Abbott *et al.*, 2005). The aim is to eliminate the non-value added activities or wastes, through the continuous improvement efforts. The results of the Demand Visibility and Operational Visibility experiments highlight that sharing information across the supply chain helps to eliminate the following types of waste (5.2.1 to 5.2.4).

5.2.1 Reduced inventory

The total inventory for the Demand Visibility and Operational Visibility experiments are shown in Table 5.1. The findings indicate that sharing the right information could reduce the inventory level progressively:

Table 5.1: The total inventory for the Demand Visibility and Operational Visibility experiments

Demand Visibility Experiment		Operational Visibility Experiment	
Scenarios	**Total Inventory**	**Scenarios**	**Total Inventory**
S1.1	683538	**S2.1**	720599
S1.2	341498	**S2.2**	664391
S1.3	586108	**S2.3**	598845
S1.4	231295	**S2.4**	420299
S1.5	183581	**S2.5**	483832

The supply chain held nearly 30% of the total customer demand as its inventory in Scenario 2.1. The supply chain inventory level for the Operational Visibility experiment decreased by:

- 7.8% after shared inventory information (Scenario 2.2) compared with shared forecast scenario (S2.1); equalling 27.3% of the total customer demand

- 10% after sharing real customer demand information (Scenario 2.3) compared with the sharing inventory scenario (S2.2); equalling 24.6% of the total customer demand
- 30% after shared operational information every week (Scenario 2.4) compared with shared real customer demand scenario (S2.3); equalling 17.3% of the total customer demand
- 19.2% after sharing operational information every two weeks (Scenario 2.5) compared with shared real customer demand scenario (S2.3), equalling 19.9% of the total customer demand

The largest contribution to inventory reduction is sharing operational information, followed by sharing real demand information. The inventory level of Scenario 2.4 was reduced by 41.7% (17.3% of the total customer demand) when sharing forecast, inventory, real demand, and operational information every week.

The inventory level decreased with the increased visibility level in the Demand Visibility experiment. Unlike the findings from the Operational Visibility experiment, Scenario 1.5 achieved the least inventory after sharing all the information with a two-week information sharing frequency. Scenario 1.4, which shared all information each week, might be expected to have the least inventory level. This may be due to a ‘learning effect’ among the role playing participants. In order to reduce the learning effect in the result, a test simulation was operated to ensure the participants had the same level of knowledge. They were required to switch roles in the experiments. However, since the scenario configurations and the simulation environment for the Demand Visibility experiment were less complex than in the Operational Visibility experiment, the participants were more likely to learn from the previous four experiments.

The results from the Demand Visibility experiments demonstrated the findings of Yao and Dresner (2008) research. They studied the effect of sharing demand and inventory status on inventory reduction, in a two-stage supply chain. This research extends their research in a four-echelon supply chain and shows the inventory reduced by 16.9% after enabling visibility on inventory and customer demand. More importantly, the Operational Visibility experiment investigated the value of sharing operational information, and shows a 30% inventory reduction in the simulation supply chain. The results indicate that improved supply chain visibility is effective for inventory reduction.

5.2.2 Reduced overproduction

Overproduction represents the total excess production over the real demand in each scenario. Figure 5.5 only illustrates the impact of visibility on overproduction for the Operational Visibility experiment since the less possible side effect of 'learning' than the Demand Visibility experiment. It lists the overproduction for the Operational Visibility experiment and shows that the overproduction from the supply chain reduced gradually from 134,085 units (S2.1) to 95,037 units (S2.4) after sharing forecast, inventory, real demand, and operational information with an increased information sharing level. Overproduction in the supply chain was reduced with increased visibility levels.

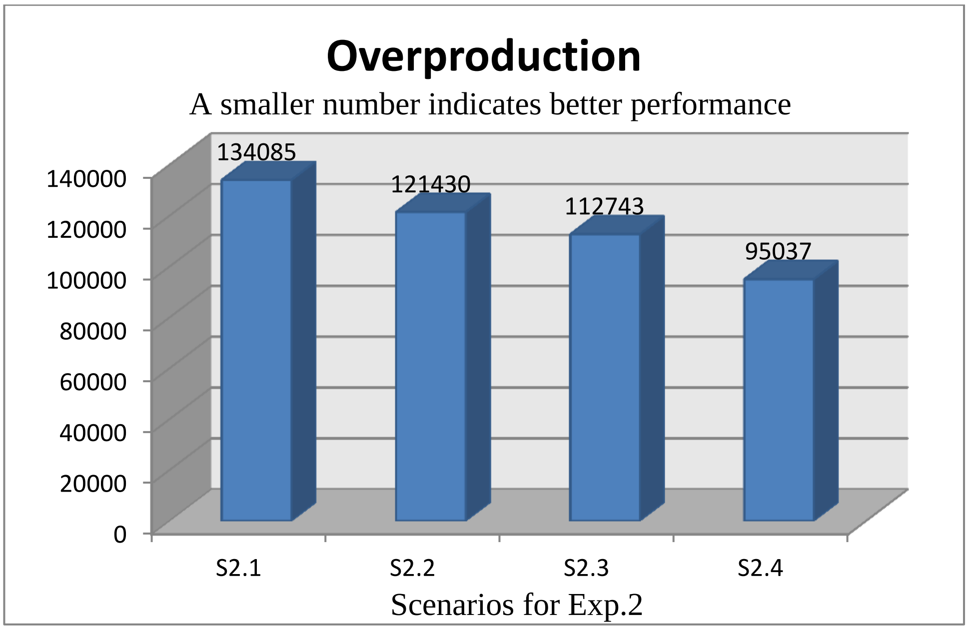


Figure 5.5: Overproduction in the supply chain for the Operational Visibility Experiment

5.2.3 Reduced costs

The supply chain total costs for this simulation were calculated from five types of cost: fixed cost, operation cost, inventory cost, extra cost, and penalty cost (see Table 4.1). Figure 5.6 shows the total costs for the Demand Visibility and Operational Visibility experiments. The horizontal axis describes the five scenarios for each experiment, and the vertical axis presents the value of the supply chain total costs; a smaller value indicates better performance. Blue represents the Demand Visibility experiment, and red, the Operational Visibility experiment. Both blue and red lines show that the total supply chain cost reduced with increased visibility in both experiments.

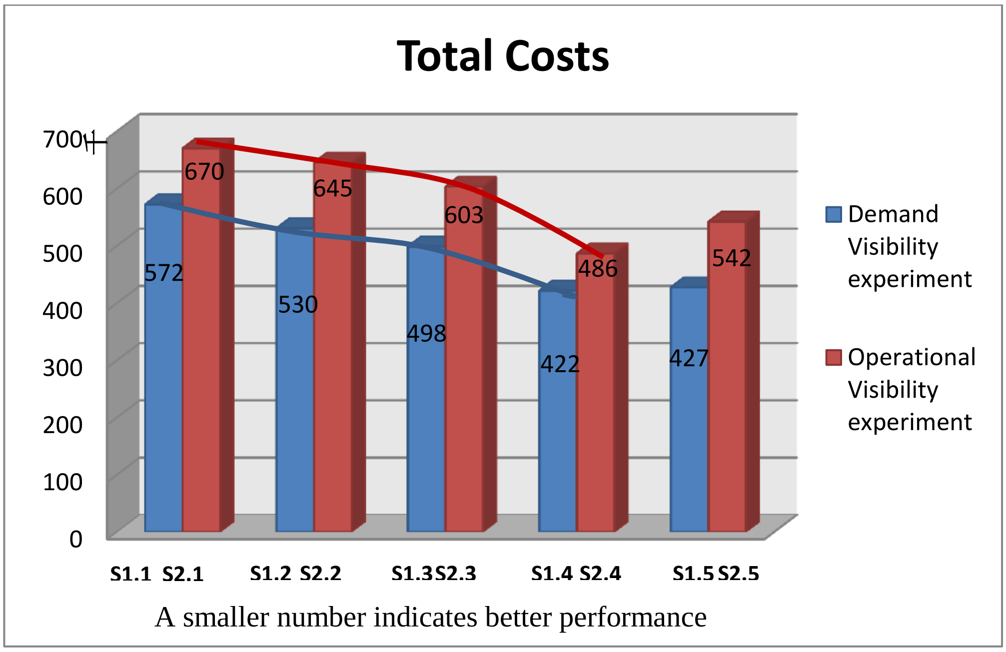


Figure 5.6: The total costs for the Demand Visibility and Operational Visibility experiments

In the Demand Visibility experiment, the total costs of Scenario 1.4 decreased by 26% compared with Scenario 1.1 after sharing forecast, inventory, and demand information every week. When the same information was shared with a two-week information sharing frequency (Scenario 1.5), the total costs increased slightly but were still lower than the shared forecast and inventory scenario (Scenario 1.3). This suggests that shared demand information is more valuable in terms of cost reduction, than shared forecast and inventory information at a higher frequency. Similarly, in the Operational Visibility experiment, the total costs were reduced from 670,000 in Scenario 2.1 to 486,000 in Scenario 2.4 when information was shared every week. When the same information was shared every two weeks, the total costs of Scenario 2.5 were higher than Scenario 2.4, but lower than Scenario 2.3 - shared real demand with one-week information sharing frequency. Thus, it appears operational information is more effective in reducing supply chain costs than sharing forecast and inventory at a higher frequency.

5.2.4 Reduction in other types of waste

Some wastes, such as waiting times and digital waste, are not measured quantitatively, but exist in supply chains. Waiting, as one of the seven wastes in lean manufacturing, is normally caused by a shortage of materials, people, equipment, or even information. For example, in the Operational Visibility experiment, increased visibility among the supply chain facilitated supply chain partners to reduce their waiting time when late delivery occurred.

Digital waste happens when irrelevant and/or inaccurate information is shared in supply chains. Digital waste can complicate and confuse decision-making. For instance, there is a demand for centralised information sharing, but without real customer demand, the information may be seen as digital waste that hampers individual decision-making processes.

The results from both experiments verified the direct and indirect effects of supply chain visibility on eliminating wastes. Sharing accurate information could help reduce unnecessary transportation during the processes and reduce the potential damage to products (Holcomb *et al.*, 2010). This research supports the result of Byrne and Heavey (2006) study, which pointed out that sharing demand and inventory information are important to 'lean' in terms of inventory reduction and total supply chain cost savings. More importantly, this research demonstrates that increased visibility in operations can further reduce by 30% the inventory, and by 19.4% the total costs, in the simulation supply chain. A reduction in inventory may however cause a decrease in agility; the next section explores the correlation between increased visibility and supply chain agility.

5.3 Visibility and agility

Supply chain agility can be viewed as a strategy which focuses on meeting unique customer needs efficiently and rapidly (Agarwal *et al.*, 2006). In order to address these changing needs responsively, a supply chain has to be ‘flexible’. So agility can be interpreted as the flexibility of supply chains in dealing with volatile market demands (Wang and Wei, 2007). As Lin *et al.* (2006) have claimed, the driver of agility in supply chain is that of ‘changes in demand’. These changes are caused by market volatility, customer requirement changes, intense competition, technological change, and changes in social factors (Yusuf *et al.*, 1999; Christopher, 2000). Besides flexibility, an agile supply chain can also be measured in term of time (time required to respond to a customer’s order) and range (answering the customer’s demand with the right product mix in the right quantity) (Closs *et al.*, 2005). Supply chain agility in this simulation was measured in terms of satisfying customer demands and the flexibility of the supply chain.

5.3.1 Customer satisfaction

Customer service levels for the Demand Visibility and Operational Visibility experiments are shown in Figure 5.7. A larger number indicates higher customer satisfaction. The results show that the customer service levels increased with enhanced supply chain visibility in both experiments. In the Demand Visibility experiment, Scenario 1.4 (S1.4) had the best customer satisfaction, and achieved 99.6% customer satisfaction after sharing forecast, inventory, and demand information every week; Scenario 2.4, likewise, had the best customer satisfaction in the Operational Visibility experiment, and its customer service levels were 98.2% which showed a 6.5% increase as compared to Scenario 2.1 after operational information was shared each week. Additionally, the supply chain achieved 99.3% of customer satisfaction in Scenario 1.5 and 96% in Scenario 2.5 after sharing the same information at a two-week information sharing frequency. Sharing the right information, such as real customer demand and operational information, is vital in terms of increasing sales and improving customer satisfaction.

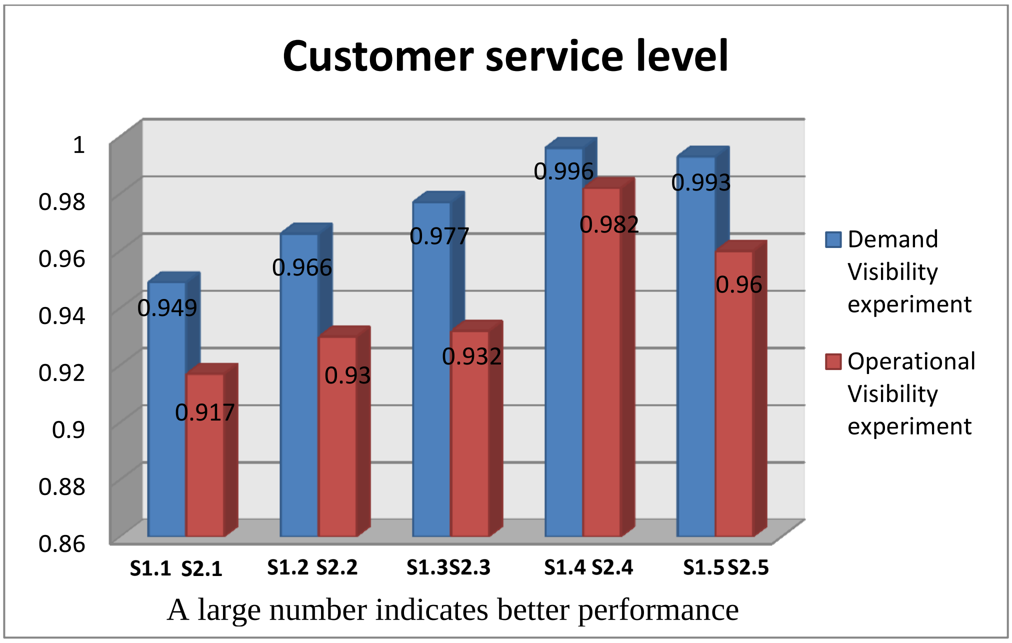


Figure 5.7: Customer service levels for the Demand Visibility and Operational Visibility experiments

A study by Simatupang and Sridharan (2001) suggested that sharing information such as order status, production schedule, inventory status, and customer data could improve the order fulfilment process, and improve customer service and satisfaction. The results obtained support their statement and demonstrated a 4.7% improvement in customer satisfaction after shared forecast, inventory and customer demand data. Furthermore, results from the Operational Visibility experiment indicated that there are improvements in customer satisfaction and flexibility when the operational information (order status, work in process, and production schedule) is available.

5.3.2 Flexibility

An agile supply chain has the flexibility to cope with changes. In this simulation, dealing with changes was viewed as dealing with supply chain disruptions. Therefore, the flexibility of the supply chain was measured by analysing backorders and the number of disruptions. The results for the Demand Visibility and Operational Visibility experiments are shown in Table 5.2. Scenario 1.4 achieved the least backorders and number of disruptions in the Demand Visibility experiment after sharing forecast, inventory and real demand information. In the Operational Visibility experiment, the number of disruption in Scenario 2.5 was less than Scenario 2.4; however, its backorders were nearly three times higher than Scenario 2.4. This means the supply chain had to deal with more backorders for each disruption in Scenario 2.5 than Scenario 2.4.

Table 5.2: The backorders and number of disruption for the Demand Visibility and Operational Visibility experiments

Demand Visibility Experiment			Operational Visibility Experiment		
Scenarios	**Backorders**	**Number of Disruptions**	**Scenarios**	**Backorders**	**Number of Disruptions**
S1.1	120826	55	**S2.1**	178947	63
S1.2	96738	62	**S2.2**	154276	55
S1.3	60366	43	**S2.3**	126960	43
S1.4	7845	19	**S2.4**	29003	28
S1.5	12216	31	**S2.5**	89682	26

A study by Wang and Wei (2007) indicated that information visibility (real time inventory and customer demand visibility) is critical for improving supply chain flexibility. Such information relating to inventory status, planning, customer demand, and performance evaluation needs to be shared swiftly and accurately. This research supports their finding and shows that the flexibility of the supply chain improves significantly, in terms of reducing backorders and supply chain disruptions, when inventory and customer demand information were shared in the Demand Visibility experiment. More importantly, the results of the Operational Visibility experiment suggest that sharing operational information is also vital for improving supply chain flexibility. The shared operational information helps supply chain partners understand each other's current status and that of the whole supply chain, and facilitates the development of the relationship and coordination to cope with 'changes'.

In summary, enabling supply chain visibility across supply chains improves supply chain agility in terms of improving customer satisfaction and flexibility. Sharing real demand and operational information makes it possible for supply chain executives to quickly respond to disruptions and prevent supply chain stoppage.

5.4 Visibility and LeAgility

The correlation between visibility, lean and agile performance has been discussed. This section investigates the effect of visibility on improved supply chain LeAgility. According to Christopher and Towill (2001), LeAgile supply chains focus on achieving the best of both cost and service levels as their market winner. In other words, they aim to increase customer service levels whilst reducing the cost. The results discussed (5.2 and 5.3) highlight the fact that information visibility enhanced the LeAgility of the experiment supply chain by improving customer service level by 6.5%, whilst reducing costs by 27.4%. Are there any other contributions from improved visibility? The supply chain total value analysis and synthesis graph analysis shows the impact of increased visibility on supply chain LeAgility from two different perspectives.

5.4.1 Supply chain total value

The supply chain total value describes the total supply chain performance metric in terms of value to the customer. The higher the value of the supply chain, the better the overall performance (see Chapter 4.6.5). The supply chain total values for the Demand Visibility and Operational Visibility experiments are shown in Figure 5.8. The horizontal axis describes the five scenarios for each experiment, and the vertical axis is the supply chain total value; a larger value indicates better overall supply chain performance. Blue is used to represent the Demand Visibility experiment and red represents the Operational Visibility results. The lines illustrate that the supply chain total value increases progressively with increased visibility in both experiments. However, the total supply chain value drops by 16.6% when all information is shared at the lower frequency in Scenario 2.5 in the Operational Visibility experiment. This highlights the effect of information sharing frequency on supply chain performance. Sharing information at a lower frequency may cause an untimely and inaccurate information flow in a supply chain. In the simulation, this information may become to be viewed as 'digital waste', hampering the supply chain partners' decision-making on forecast and production plans.

The supply chain that focuses on granting a high total value to the customer is described as the best value supply chain by Ketchen *et al.* (2008). Their research highlighted that the best value supply chains improve their performance by delivering high total values to customers in terms of speed, cost, quality, and flexibility. This research demonstrates that increased visibility across supply chains could help to achieve high supply chain total value by reducing total costs and improving flexibility. High supply chain total value was achieved by focusing on eliminating waste (5.2) and improving agility (5.3) in the simulation supply chain.

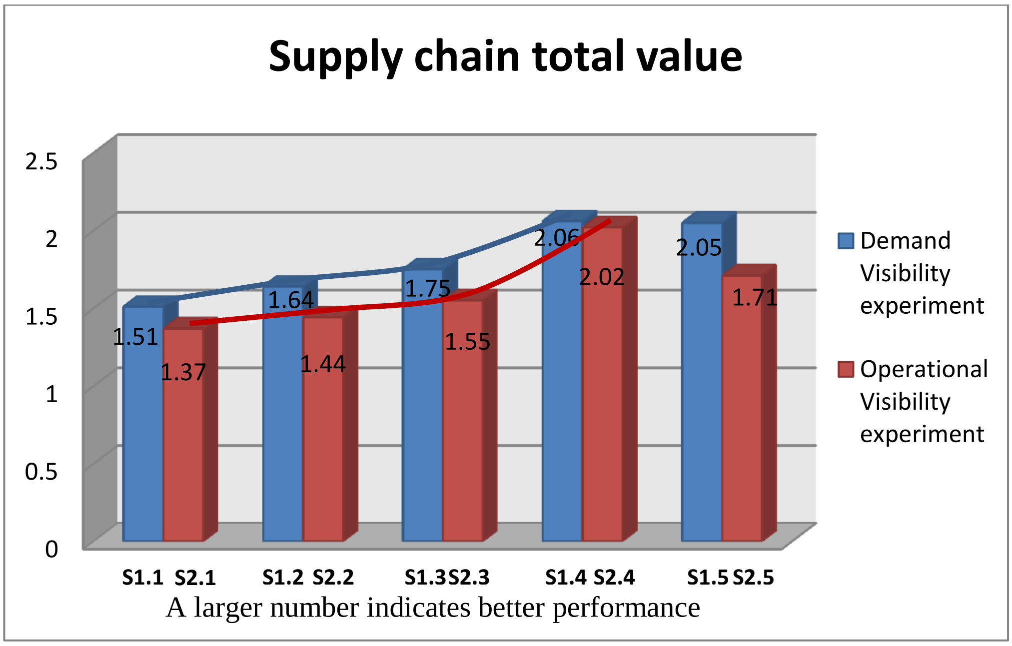


Figure 5.8: the supply chain total value for the Demand Visibility and Operational Visibility experiments

5.4.2 Synthesis graph analysis

The supply chain total value shows to what extent increased visibility improves the supply chain LeAgility in terms of quality, service level, costs and lead time. It cannot provide information such as flexibility, profitability, and forecast accuracy. Therefore, synthesis graph analysis was created to compare the supply chain performance in different scenarios for the Demand Visibility and Operational Visibility experiments. It shows the results of each measure of the performance measurement framework (Table 2.3) in a visual graph based on their ranking (see Appendix 6). A LeAgile supply chain should have the best overall rank in both lean and agile measures.

5.4.3.1 Synthesis graph for the Demand Visibility Experiment

The results for the Demand Visibility experiment are illustrated in Figure 5.9. The vertical axis shows supply chain performance rank; and the number one indicates the best performance. The horizontal axis describes each measure of the performance measurement framework. Five colours are used to show the performance of each scenario respectively.

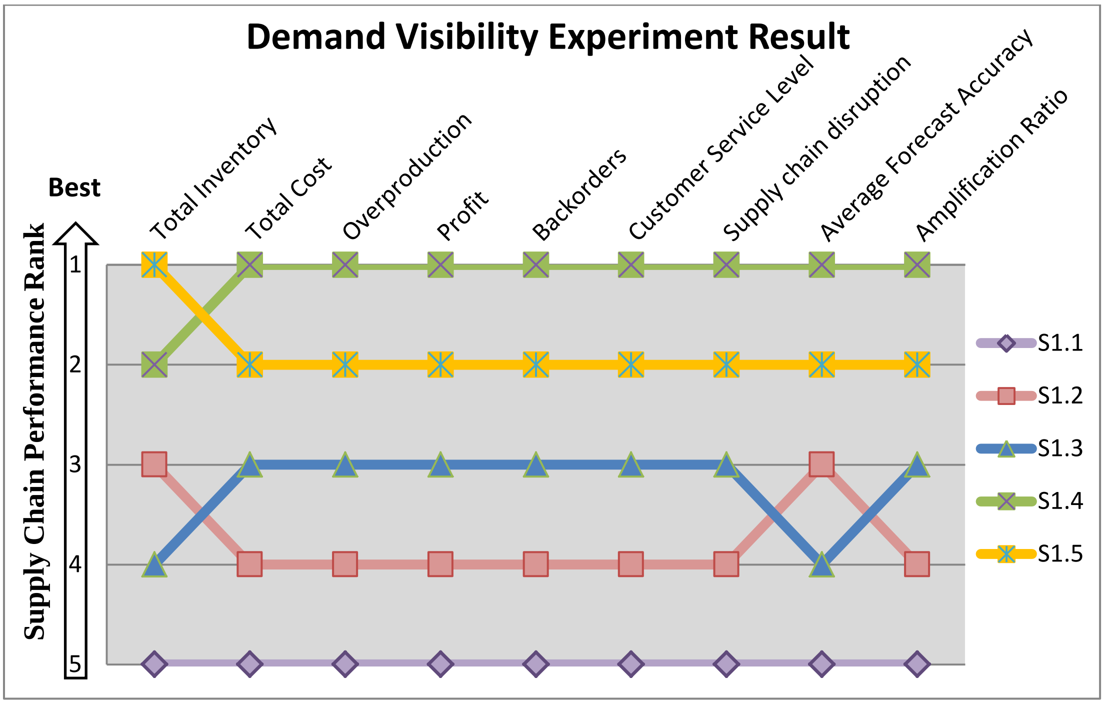


Figure 5.9: The result for the Demand Visibility experiment

It may be seen that scenario 1.4, which had full visibility with a one week information sharing frequency, is ranked as the best performance for most performance measures, with the exception of Total Inventory. One reason for the fact that Scenario 1.5, at the lower information sharing frequency, held the lowest inventory level could be a ‘learning effect’ (Table 5.1), although the participants were required to switch roles to avoid memorising the simulation configurations. However, since the simulation configurations and environment in the Operational Visibility experiment were more complex than in the Demand Visibility experiment, any ‘learning effect’ was reduced, and Scenario 2.4 with higher information sharing, held the least inventory (Figure 5.9).

The Scenario 1.3 was expected to achieve a better LeAgility than Scenario 1.2 when the inventory status was shared. However, the supply chain in Scenario 1.3

held more inventory than Scenario 1.2. This may have been a result of inaccurate forecast in Scenario 1.3 (Figure 5.3). Graman and Sanders (2009) compared the contributions to inventory reduction, both by postponement strategy and forecast accuracy, and found that both strategies resulted in inventory reduction, whilst maintaining constant customer satisfaction levels. The inaccurate forecast in Scenario 1.3 affected the participants' decisions on inventory. As discussed in Figure 5.3 (page 85), poor information quality is probably the main reason. In the simulation supply chain, sharing inventory information without accessing the customer demand affects the production forecast and inventory planning.

5.4.3.2 Synthesis graph for the Operational Visibility Experiment

The results from the Operational Visibility experiment are illustrated in Figure 5.10. Similar to Figure 5.9, the supply chain achieved the best performance in Scenario 2.4, which had the full visibility configuration at a one-week information sharing frequency; although Scenario 2.5 had slightly better performance on the 'Out of Stock'. Table 5.2 shows the total backorders and supply chain disruptions in the Operational Visibility experiment. The total number of disruptions (including material flow and out of stock disruption) in Scenario 2.5 was less than Scenario 2.4; however, the total backorders in Scenario 2.5 were around three times more than Scenario 2.4. The supply chain had to cope with more backorders for each disruption in Scenario 2.5.

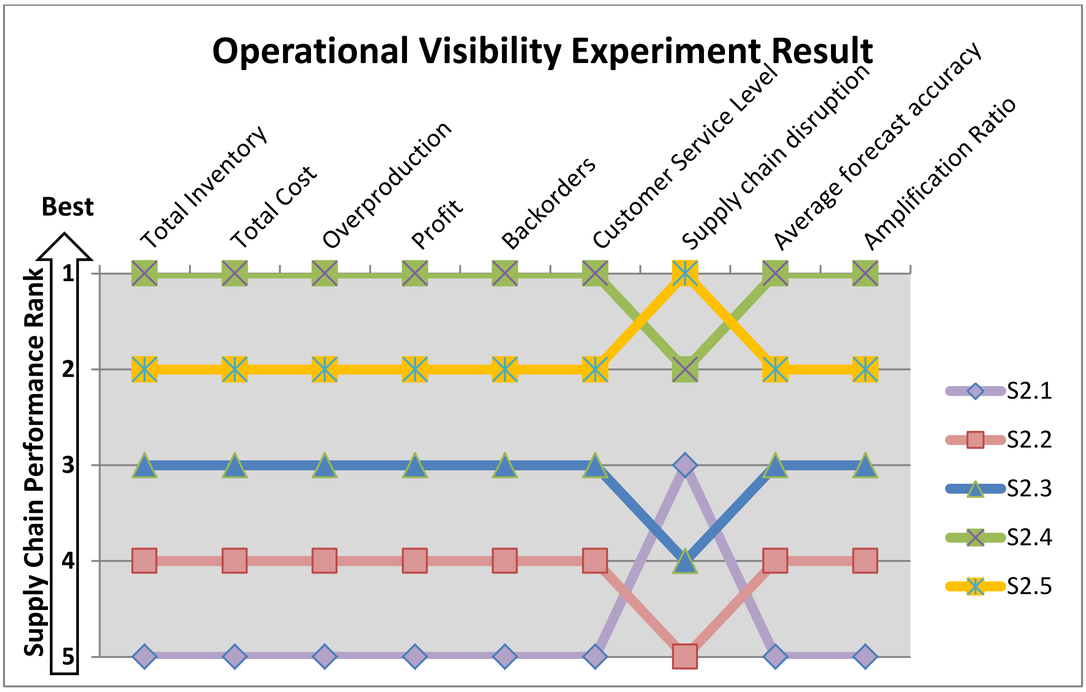


Figure 5.10: the result for the Operational Visibility experiment

In summary, the results from the experiments have shown supply chain visibility to be an effective approach to boosting supply chain LeAgility. Barratt and Oke (2007) demonstrated that a high level of visibility on demand and process could bring a sustainable competitive advantage to supply chains. This research shows that the simulation supply chain achieved competitive advantages by becoming leaner with 41.7% less inventory and 27.5% less total costs, and more agile, with 6.7% more customer satisfaction and improved flexibility, when customer demand and operation information were shared. This information helped supply chain partners to reduce costs and wastes without affecting customers. Accessing operational information increases the flexibility to enable a better response to supply chain disruptions.

A visibility measurement model was developed by Caridi *et al.* (2010) to quantify visibility level in a supply chain. It can be used as an assessment tool to determine the current visibility level of a supply chain, and identify the area most urgently needing to improve in visibility. The outcome of this research can be used as a complement for their visibility measurement model, which helps supply chain executives cope with the question of 'how to improve visibility'. The correlation between four different visibility levels and their corresponding supply chain LeAgility is shown in Table 5.3. Symbols ● (increased performance) and ○ (decreased performance) are used to indicate the lean and agile performances of each visibility level.

Table 5.3: Supply chain visibility and LeAgility

	Forecast	+ Inventory	+ Real Demand	+ Operational Information
Leanness				
Total Costs	●	●●	●●●	●●●●
Total Inventory	●	●●	●●●	●●●●
Overproduction	●	●●	●●●	●●●●
Non-value added processes			●	●●
Material flow	●	●●	●●●	●●●●
Profit	●	●●	●●●	●●●●
Digital waste	—	○	●	●●
Agility				
Customer service level	●	●●	●●●	●●●●
Supply chain disruption	●	●●	●●●	●●●●
Flexibility	—	—	—	●

●: improved performance ○: decreased performance —: None

5.5 The advantages of the supply chain visibility approach

The results discussed have suggested that supply chain visibility is an effective approach to improving supply chain LeAgility. Experiment Three (Decoupling Point and Postponement experiment) was designed to identify the advantages of the supply chain visibility approach over the decoupling point and late customisation approaches, for establishing a LeAgile supply chain. In order to adopt the decoupling point and late customisation approaches, the original supply chain from the HP case study was modified to produce standard products which are then customised at a late stage. Two material decoupling points and one information decoupling point were integrated into the model. The information decoupling point was enabled from the second tier supplier, and the material decoupling point (known as strategic inventory), had been placed between the Assembly factory and the Distribution centre (Figure 4.6, Chapter 4). The scenarios of Experiment Three and their strategies are shown in Table 5.4.

Table 5.4: scenarios of Experiment Three - Decoupling Point & Visibility Experiment

	Strategy	**Supply chain type**	**Forecast**	**Inventory**	**Real demand**	**Unexpected event**
S 3.1	Information DP (Demand Visibility)	Original	√	√	√	×
S 3.2	Material decoupling point (postponement)	Modified	√	√	×	×
S 3.3	Information decoupling + Material decoupling	Modified	√	√	√	×
S 3.4	Postponement + visibility	Modified	√	√	√	√
S 3.5	Visibility	Original	√	√	√	√

The benefits of the decoupling point and postponement approaches have been extensively discussed in literature (Chapter 2.2). However, the contribution of the supply chain visibility approach towards creating LeAgile supply chains has not been so well clarified. These experiments identify the comparative advantages of the supply chain visibility approach from four aspects: the bullwhip effect, leanness, agility, and LeAgility.

5.5.1 Bullwhip effect

The results from the Demand Visibility and Operational Visibility experiments have already shown that improved information visibility successfully reduced the bullwhip effect in the simulation supply chain (5.1). The bullwhip effect for the decoupling point and late customisation approaches is shown in Figure 5.10. The vertical axis presents the five scenarios for Experiment Three; the horizontal axis shows the value for performance measures in reducing the bullwhip effect. A smaller value number indicates better performance; and their performances are ranked. Results illustrate that both visibility approach scenarios (S3.4 and S3.5) produced better performance in the bullwhip effect elimination than the other scenarios. This suggests that supply chain visibility approach was more successful at reducing the bullwhip effect in the simulation supply chain than the decoupling point and late customisation approaches. Figure 5.11 also illustrates that the demand amplification ratio in Scenario 3.4 decreased by 3% more than Scenario 3.5, and forecast accuracy improved by 11%. This means that adopting supply chain visibility in a postponement strategy supply chain could further reduce the bullwhip effect. It supports the findings of Chen and Lee (2009) study that sharing information, together with order postponement strategy, reduces the bullwhip effect.

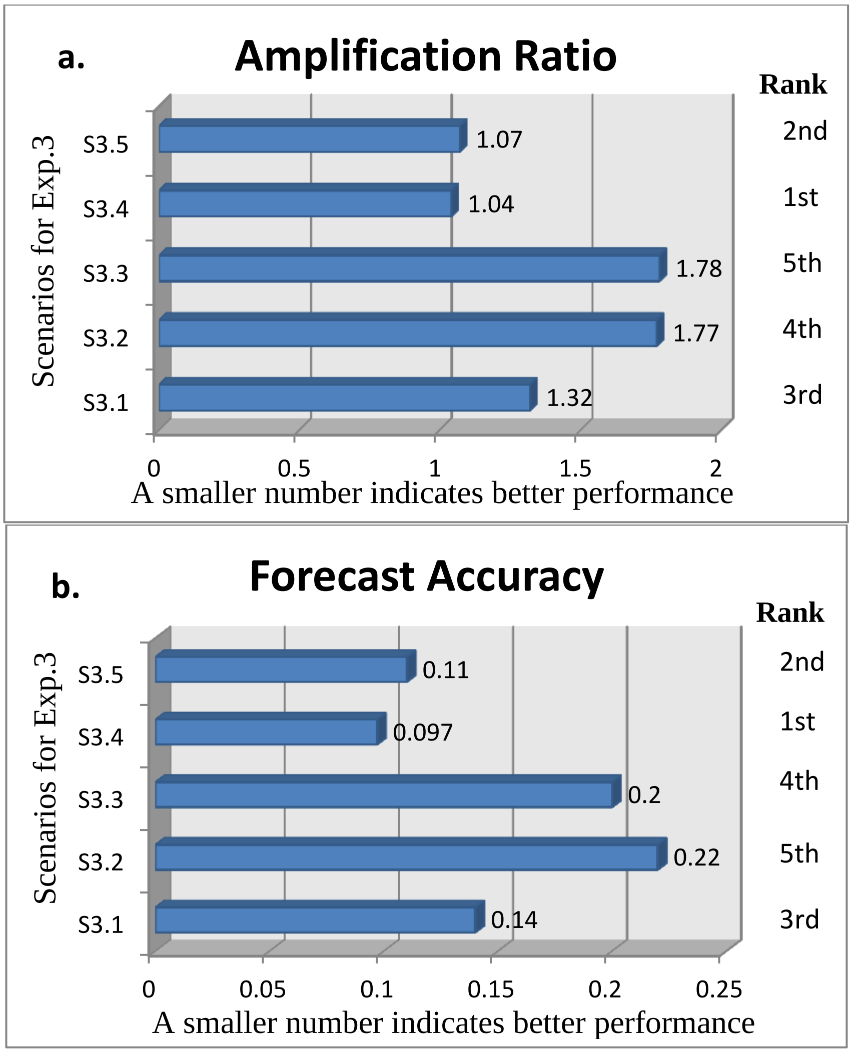


Figure 5.11: The bullwhip effect for Experiment Three - Decoupling Point & Visibility Experiment

5.5.2 Leanness

Results from the Demand Visibility and Operational Visibility experiments have already demonstrated the effect of supply chain visibility on the elimination of wastes. The following sections show the impact of the decoupling point and late customisation approaches on lean performance.

5.5.2.1 Cost reduction

The supply chain total cost for Experiment Three (Decoupling Point & Visibility Experiment) is illustrated in Figure 5.12. The impact of the decoupling point and the late customisation approaches on cost reduction has been well discussed. A study from Sun *et al.* (2008) indicated that the cost of the supply chain network was reduced after placing multiple decoupling points to partition the supply chain network. Scholten *et al.* (2010) studied the Humanitarian Aid (HA) supply chain and suggested that the HA should adopt a postponement strategy in allocating its relief supplies in some countries, in order to reduce inventory and operation costs. In this experiment, the supply chain total cost in visibility strategy scenarios (S3.4 and S3.5) was nearly 24.3% less than in the decoupling point strategy scenario (S3.2) and late customisation strategy scenario (S3.3). Furthermore, the total supply chain cost in Scenario 3.4 (Postponement + Visibility strategy) is slightly less than that of Scenario 3.5. One possible reason could be that product standardisation, as an outcome of postponement strategy, reduces the inventory cost in Scenario 3.4.

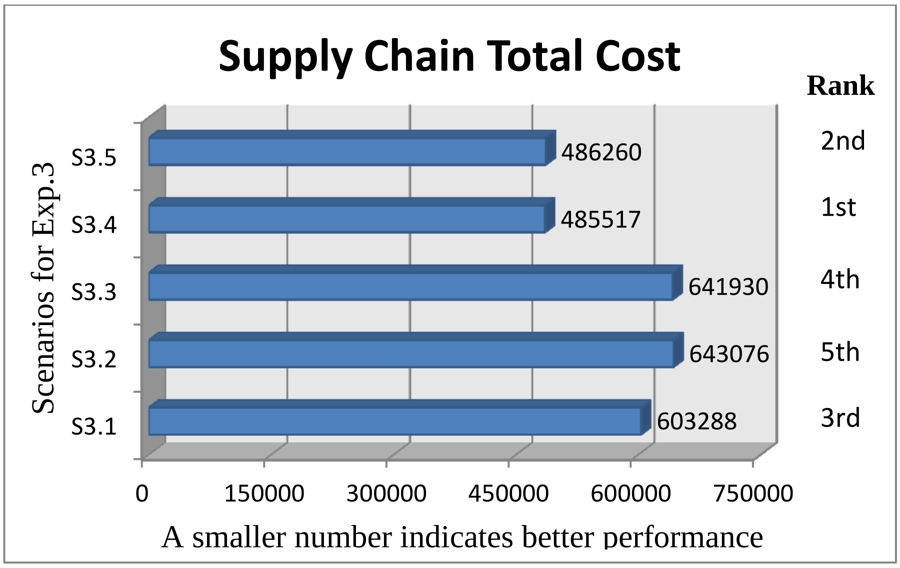


Figure 5.12: Supply chain total cost for Experiment Three

5.5.2.2 Inventory reduction

The supply chain's total inventory of each scenario for Experiment Three is shown in Table 5.5. The total inventory of the supply chain was reduced after enabling visibility across the supply chain (Scenario 3.4 and Scenario 3.5). Scenario 3.4, which is the visibility and postponement approach scenario, held the lowest inventory level in the experiment. The total inventory in Scenario 3.4 decreased by 36.9% and 28% compared with the decoupling point (S3.2) and late customisation scenarios respectively (S3.3). Having delayed production (late customisation) allowed the supply chain to postpone producing the final product until the last minute, and provides numerous benefits, such as decreased inventory and cost (Mason-Jones and Towill, 1999; Christopher and Towill, 2000; Graman and Sanders, 2009). This could explain why the inventory level in Scenario 3.4 (visibility and postponement approach) was lower than Scenario 3.5, even though the same visibility level was applied.

Table 5.5: Total inventory for decoupling point & visibility experiment

Decoupling point & Visibility Experiment	
Scenarios	**Total Inventory**
S3.1	598845
S3.2	646832
S3.3	566788
S3.4	408156
S3.5	420299

Overall, the supply chain visibility approach achieves leaner supply chain performance than the decoupling point and late customisation approaches in terms of reduced cost and inventory. Furthermore, this research suggests a strategy that combines the supply chain visibility approach with a postponement strategy, could further improve the leanness of the supply chain, as the leanest supply chain (Scenario 3.4) was achieved after enabling supply chain visibility in a postponement structured supply chain.

5.5.3 Agility

The results from the Demand Visibility and Operational Visibility experiments demonstrated that enabling supply chain visibility across supply chains improves supply chain agility in terms of improving customer satisfaction and flexibility. The following sections show the customer satisfaction and supply chain flexibility for the different approaches.

5.5.3.1 Customer satisfaction

The customer service levels for Experiment Three (Decoupling Point & Visibility Experiment) is shown in Figure 5.13. It shows that Scenario 3.5 - the visibility strategy scenario - achieved 98.2% customer satisfaction which was the second highest in the experiment. Additionally, the customer service level increased by 0.5% after adopting the visibility strategy in a postponement supply chain. The supply chain had higher customer satisfaction in both visibility approach scenarios (S3.4 and S3.5), than in the decoupling point and late customisation approaches scenarios (S3.1, S3.2, and S3.3).

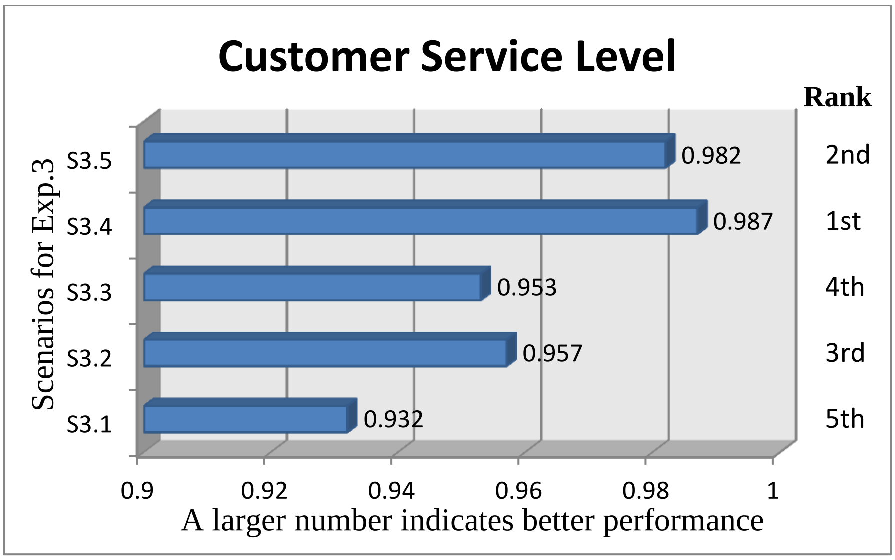


Figure 5.13: Customer service level for Experiment Three – Decoupling point & Postponement Experiment

5.5.3.2 Flexibility

Supply chain flexibility in this simulation can be derived by considering the backorders and the number of disruptions. The flexibility of the supply chain for the Decoupling Point & Postponement experiment is illustrated in Table 5.6. The backorders of both visibility scenarios (Scenarios 3.4 and 3.5) were much less than those of the other approaches' scenarios. The flexibility of the simulation supply chain in Scenario 3.4 was improved after enabling visibility in a postponement supply chain. However, Scenario 3.2 had only twenty-three cases of disruption after the two material decoupling points were placed near the distribution centres. The supply chain in Scenario 3.2 was flexible enough to cope with the demand variation since it held the highest inventory stock in the experiment (Table 5.4). However the inaccurate forecast in Scenario 3.2 (Figure 5.10b) resulted in a larger amount of backorders than Scenario 3.4 and 3.5.

Table 5.6: The backorders and numbers of disruption occurrences for Decoupling Point & Postponement Experiment

Scenarios	Total backorder	Number of disruption	Performance Rank
S3.1	126960	55	5
S3.2	94924	**23**	3
S3.3	112678	46	4
S3.4	**18972**	25	1
S3.5	29003	28	2

A study by Graman and Sanders (2009) indicated that compared to improving forecast accuracy, late customisation strategy is more appropriate in achieving agility in terms of inventory reduction whilst maintaining constant customer satisfaction. However, results from the Experiment Three (Decoupling Point & Postponement Experiment) suggest that enabling visibility across supply chains is more effective for improving supply chain agility. Supply chain visibility has advantage over the decoupling point and late customisation approaches in terms of increased customer satisfaction and flexibility. This research also demonstrated that the supply chain becomes more agile after enabling the same visibility level in a postponement supply chain.

5.5.4 LeAgility

The supply chain achieved the best lean and agile performance in Scenario 3.4, after adopting the visibility and postponement strategy. The supply chain total value measure was used to show to what extent visibility improves supply chain LeAgility.

The supply chain total value of each scenario for Experiment Three - the Decoupling Point & Postponement Experiment - is shown in Figure 5.14. It highlights that the performance of both visibility strategy scenarios (Scenario 3.4 and Scenario 3.5) was significantly better than the decoupling point strategy and postponement strategy scenarios. The total value of Scenario 3.5 was slightly lower than that of Scenario 3.4, but much better than that of the other scenarios. The supply chain achieved its best LeAgility by enabling information visibility with a postponement strategy supply chain.

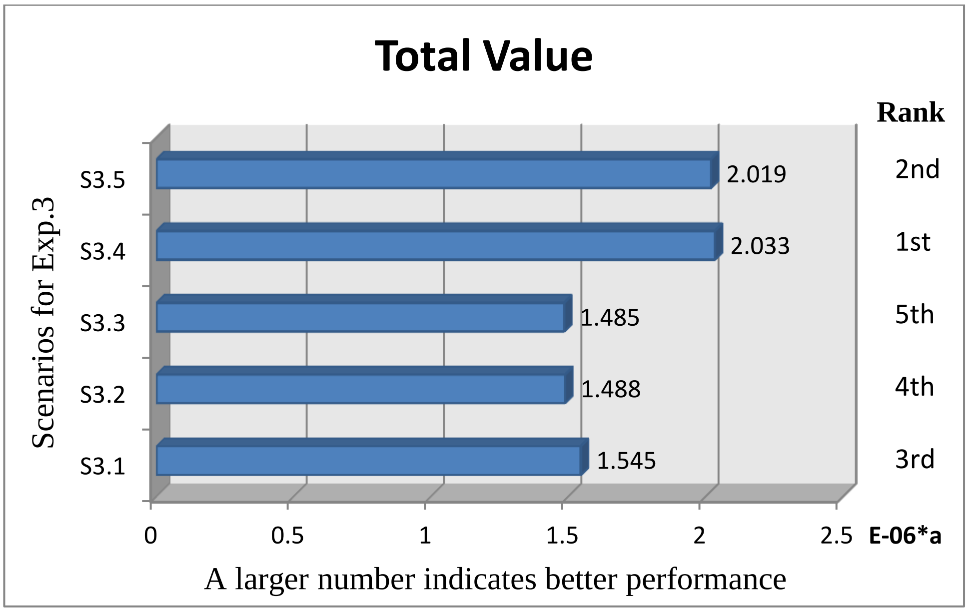


Figure 5.14: The supply chain total value of Experiment Three

The decoupling point and late customisation approaches are considered to be effective tools to achieve LeAgility in certain types of supply chain. For example, Huang *et al.* (2002) proposed that a LeAgile supply chain try to achieve mass customisation by postponing product customisation until the last minute. Rahimnia and Moghadasian (2010) studied a hospital supply chain and discovered that more patients were served and the lead time and costs were reduced after implementing three decoupling points in a hospital supply chain. Differing from their studies, this research improves supply chain LeAgility by enabling visibility. Table 5.7 shows the advantages of the decoupling point, postponement and visibility approaches in the measures of lean and agile when creating LeAgile supply chains. It indicates that information visibility applied with a postponement strategy has the advantages in achieving supply chain LeAgility, more so than the other approaches in this research. Implementing a postponement strategy can be very costly in terms of product and supply chain redesign. Implementing supply chain visibility brings many of the same advantages at a significantly lower cost.

Table 5.7: the advantages of decoupling point, postponement and visibility approaches

	Lean		Agile	
	Cost	Inventory	Customer satisfaction	Flexibility
Decoupling point	●	●	●●	●●
Postponement	●●	●●	●	●
Visibility	●●●	●●●	●●●	●●●
Visibility and postponement	●●●●	●●●●	●●●●	●●●●

As suggested by Naylor *et al.* (1999) a postponement strategy has the greatest potential to achieve LeAgility in a mass production supply chain. The supply chain model used in this simulation was an ideal supply chain to implement postponement strategy. However, the supply chain total value of Scenario 3.4 (visibility and postponement) increased only by 0.6%, more than Scenario 3.5 (visibility approach). This suggests that implementing postponement strategy contributed the 0.6% increase. And this 0.6% increase is based on the assumption of zero cost of implementing the postponement approach. Thus, enabling visibility plays a vital part in increasing supply chain total value in the visibility and postponement approach scenario (S3.4). Table X shows the The supply chain visibility approach therefore has a number of advantages over the decoupling point and late customisation approaches when creating a LeAgile supply chain.

5.5 Summary

The results from the three experiments conducted suggest three major contributions to understanding LeAgility. First, this research shows that increased supply chain visibility can be an effective approach to improving supply chain LeAgility. Second, this research shows the advantages of the supply chain visibility approach over the decoupling point and postponement approaches in the move towards LeAgility. Finally, the research demonstrates the correlation between increased visibility levels and improved supply chain performance.

6

Discussion

The decoupling point and postponement strategies are the most discussed strategies in literature for creating a LeAgile supply chain. However, the previous chapter has demonstrated that supply chain visibility enabled by low cost internet technology offers advantages over these approaches when creating LeAgile supply chains (see Table 5.7). The application of supply chain visibility used in this research has been implemented into two case studies:

1. The West Midlands Collaborative Commerce Marketplace (WMCCM)
2. The European Union Factory of the Future research project IMAGINE

These are examples of the Collaborative Network Breeding Environments as forecast by the ECOLEAD, EU framework 6 research project.

ECOLEAD vision:

"In ten years, in response to fast changing market conditions, most enterprises and specially the SMEs will be part of some sustainable collaborative networks that will act as breeding environments for the formation of dynamic virtual organizations."

6.1 Visibility and supply chain performance

The relationship between increased visibility and improved supply chain performance has been discussed from both theoretical and practical perspectives (Barratt and Oke, 2007; Bartlett *et al.*, 2007; Holcomb *et al.*, 2010). Bartlett *et al.* (2007) studied the Rolls-Royce supply chain and demonstrated that exchanging high quality information through an internet-based platform improved its capacity planning, material ordering, and inventory management. In addition, Barratt and Oke (2007) explored five case studies and showed that the simulation supply chain gained a sustainable competitive advantage through high levels of supply chain visibility. In particular, the research of Holcomb *et al.* (2010) identified that reduced operation costs along with increased customer satisfaction is the competitive advantage granted by improving visibility.

However, previous research has not shown the correlation between increased visibility and improved supply chain performance. A contribution of this research is to quantify the correlation between increased visibility and improved supply chain performance. The results show a significant correlation in supply chain LeAgility with the degree of visibility, but it is not a linear relationship. Sharing more information at higher frequency will increase the visibility of the supply chain; however it does not necessarily mean a better supply chain performance. This phenomenon may be explained by two key elements of supply chain visibility: information sharing frequency and shared information.

6.1.1 Information sharing frequency (heartbeat)

Information sharing frequency (often called heartbeat or drumbeat) is one of the key elements for implementing visibility in supply chains. An appropriate information sharing frequency can provide enough operational information about the supply chain status, whilst keeping costs down. Supply chain uncertainty plays a vital role in identifying information sharing frequency. For example, the business environment simulated in the Operational Visibility experiment was much more complex than the Demand Visibility experiment. Supply chain uncertainty was significantly higher in the Operational Visibility experiment once the unexpected events were incorporated. Figure 6.1 shows the supply chain total value with different information sharing frequency for the Demand Visibility and Operational Visibility experiments. The supply chain total value in the Demand Visibility experiment increased by only 0.5% after changing the information sharing frequency from 2 weeks (Scenario 1.5) to 1 week (Scenario 1.4). Increasing the information sharing frequency had a very small improvement in terms of leanness; but it improved supply chain flexibility for the simulation supply chain (Table 5.2). However, when the supply chain uncertainty increased in the Operational Visibility experiment, a higher information sharing frequency (Scenario 2.4) improved the supply chain total value by 15.3%.

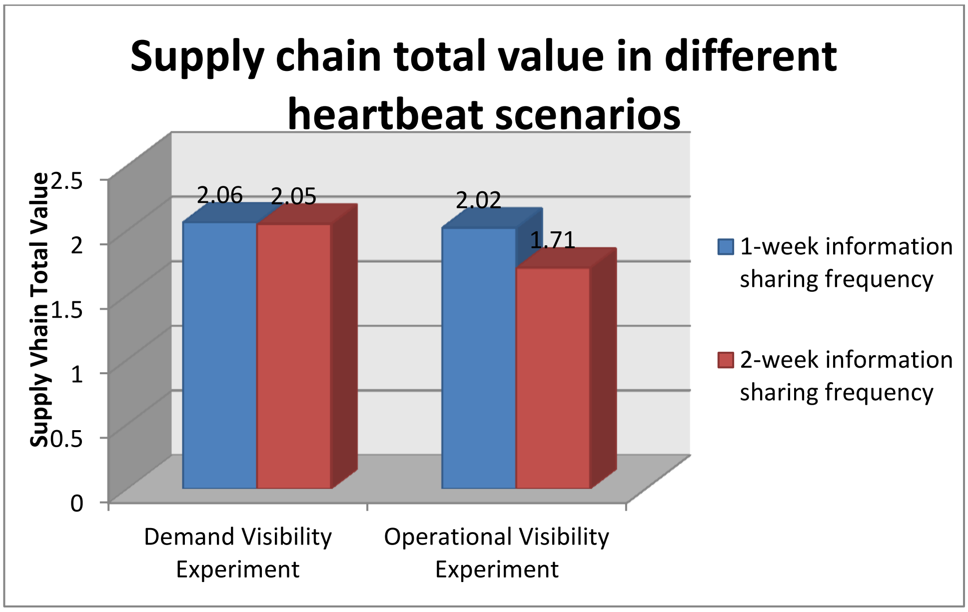


Figure 6.1: Supply chain total value in different heartbeat scenarios for the Demand Visibility and Operational Visibility experiments

This suggests that there may be a ‘critical’ information sharing frequency for each supply chain. This ‘critical’ frequency depends on the supply chain lead time and the uncertainty level. Sharing information at the ‘critical’ frequency will cause supply chains to their most LeAgility. If the information rate is higher than the ‘critical’ frequency, the supply chain may be more visible, but suffer extra resource expenses; an information rate below ‘critical’ will reduce decision making quality and resulting the performance.

6.1.2 Sharing more information or at a higher frequency

Supply chain executives have to address this question when they implement supply chain visibility: should we share more information content or share information with higher frequency, or both? The results from the Operational

Visibility Experiment suggest that the information content is more important than information sharing frequency. For instance, sharing the right information content with a two-week information sharing frequency (Scenario 2.5) achieved a better LeAgile supply chain performance than those scenarios with a one-week information sharing frequency (Scenario 2.3, 2.2, 2.1).

However, sharing information is not always a case of ‘the more the better’. Sharing non-value added information can waste resources, and is termed ‘digital waste’ (Abbott *et al.*, 2005). Digital waste can complicate and confuse decision-making. For example, the forecast accuracy in Scenario 1.3 for the Demand Visibility experiment decreased after inventory information was shared (Figure 5.2). One possible reason could be that sharing inventory information without accessing the customer demand information may be seen as digital waste that worsens the forecast of the suppliers. The right information at a lower frequency is better than more information at a higher frequency – maybe because people are unable to process it into decision making and hence it incorporates more digital waste.

6.1.3 Summary

The main outcome of this research is the correlation between information visibility and improved supply chain LeAgility. The author identified three stages of correlations between visibility level and increased supply chain LeAgility:

1. Stage one: supply chain LeAgility appears to have a leaner correlation with the degree of visibility, and becomes most LeAgile at the visibility level ν_1.
2. Stage two: supply chain LeAgility does not improve significantly when continuously increasing the visibility level from ν_1 to ν_2 (the critical visibility level). For example, in the demand visibility experiment, the supply chain becomes most LeAgile in Scenario 1.5 with a two-week information sharing frequency; however, in Scenario 1.4, the supply chain LeAgility improved only by 0.5% (Figure 6.1) when increased the information sharing frequency to every week.
3. Stage three: supply chain LeAgility decreases with the increasing visibility level. In order to become more visible, supply chains need to use extra resources, such as further investment in IT systems, employee training, or the vertical integration of the supply chain. These extra resources diminish overall supply chain performance through a loss in 'lean'.

6.2 Visibility and individual performance

The previous section discussed the relationship between supply chain visibility level and the increased LeAgility from the perspective of the entire supply chain. However, what happens to the performance of individual supply chain partners at an increased degree of visibility? This section explores the correlation between visibility and individual actor performance. The supply chain total value analysis

(Chapter 4.6.5) was also used to analyse the individual actor performance, in order to compare individual performance variations with overall performance. It represents the total performance of individual actors in terms of value to their customers.

The supply chain total value of each participant in the Operational Visibility Experiment is shown in Table 6.1. The best performance of each participant is highlighted. The results show that the entire supply chain achieved its best LeAgility in Scenario 2.4, after sharing demand and operational information each week; however, the results in Table 6.1 indicate that only four out of six participants achieved their best performance in Scenario 2.4, the exceptions being Participants 2 and 5. Participant 2 had his/her best performance in Scenario 2.2, which shared forecast and inventory each week, and Participant 5 achieved his/her best performance in Scenario 2.5, which had a full visibility configuration with a two-week information sharing frequency. Within the same information sharing frequency (S2.1 to S2.4), the performance of each participant fluctuated. One possible reason for this could be that because of visibility the participants were more inclined to make their decisions for the benefits of the entire supply chain, rather than for themselves. This suggests that sharing operational information encourages them to make decisions that are optimal for the whole system, even when they themselves may well lose out.

The implication of these findings may be difficult to implement in a business; supply chain partners are unwilling to be the ones who lose in real business, unless some form of compensation systems are applied to the supply chain, and this requires supply chain partners to focus on trust building and long-term relationship development. The reason for this phenomenon may be complex, but in general trust building is vital for developing a long-term relationship. The next section explores the relationship between visibility and trust, in order to better understand the participants' responses in the experiments.

Table 6.1: Total value of each participant in Operational Visibility Experiment

Scenario	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6
S2.1	8.16	8.13	5.25	5.33	1.69	2.04
S2.2	8.07	9.64	5.44	5.41	2.43	1.71
S2.3	8.65	9.45	6.56	5.77	2.56	1.68
S2.4	10.7	9.42	9.22	8.33	5.8	2.44
S2.5	8.93	8.45	7.76	6.6	6.26	1.67

6.3 Visibility and trust

Some researchers believe that supply chain visibility is hard to implement because it relies on trust (Pereira, 2009). Since competition seems to lie at the core of most businesses, there is a general dislike of giving away information about one's own capability and status, in case others use it to their own private advantage. The simulation results suggest a complex relationship between trust and visibility. Each can enhance the other, but they can also each compensate for lack of the other.

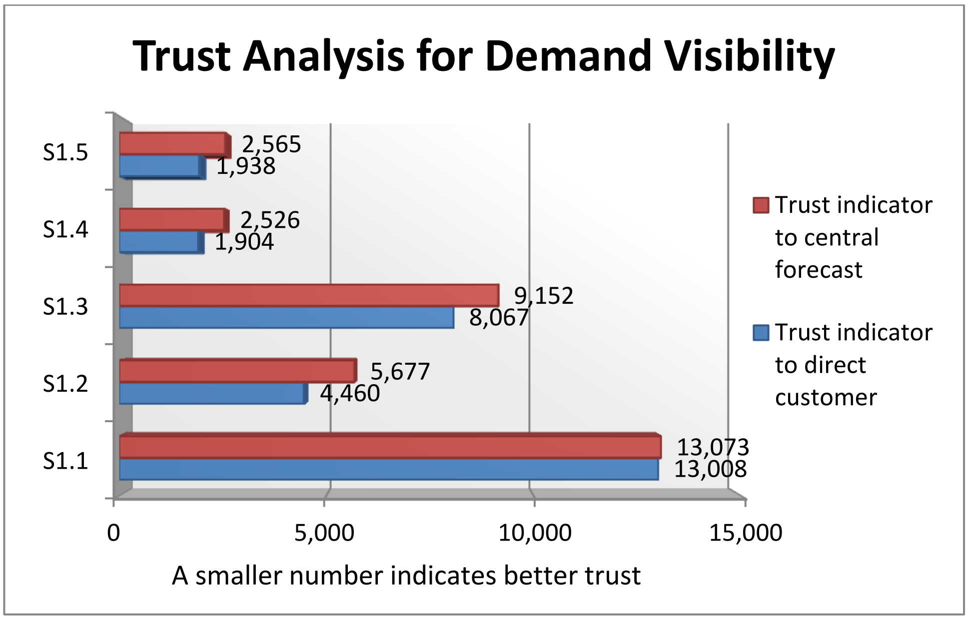


Figure 6.3: Trust analysis for Demand Visibility experiment

The trust indicators (Chapter 4.6.2) for each scenario in the Demand Visibility experiment are illustrated in Figure 6.3. They show the distance between each participant's production plan and centralised forecast or the forecast from direct customers. A smaller number implies stronger trust. The vertical axis shows the five scenarios (these correlate to visibility level) in the experiment; the horizontal axis presents the value of the trust indicators. The red bar shows the participant's trust value towards the central forecast, and the blue bar is the trust value towards their direct customers. Scenario 1.4 had the highest overall trust. With increased information visibility, supply chain partners show growing trust in both the central forecast and their direct customers, except for in Scenario 1.3. Figure 5.2 (Chapter 5.1) shows that the forecast in Scenario 1.3 was less accurate than in Scenario 1.2 after inventory status was shared. This inaccurate forecast information seemed to affect the supply chain partners' decisions and obstructed trust building. The trust indicators for each scenario also highlight that the participants preferred to follow the forecast from their direct customers, rather than from a central forecast. A study by Handfield and Bechtel (2002) suggested that a continued commitment to communication through such methods as site visits, joint production development, and sharing sensitive information leads to stronger supplier-buyer relationships. This research suggests that increasing information visibility, and specifically in the case of inventory and customer demand information, enabled stronger customer-supplier relationships.

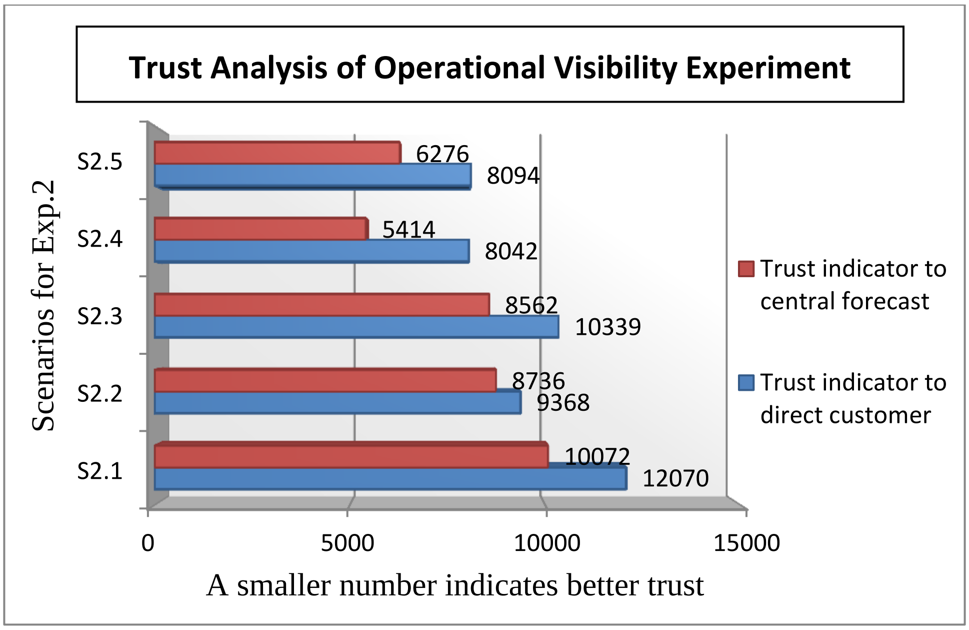


Figure 6.4: Trust analysis for Operational Visibility experiment

The trust indicators for supply chain partners in the Operational Visibility experiment are illustrated in Figure 6.4. They suggest that supply chain partners show growing trust in both the central forecast and their direct customers with the increased visibility, and the supply chain had the strongest overall trust in Scenario 2.4. The smaller trust indicator value of the red bar indicates that the supply chain partners trusted the centralised forecast instead of the forecast from their direct customers, in the Operational Visibility experiment. The change in the supply chain partners' behaviours is explained in Figure 6.5. It shows the discrepancies between Participant 4's (the assembly factory) forecast and purchase orders from the perspective of Participant 2. A smaller value indicates that the purchase decisions of Participant 4 were made based on his/her forecast. Figure 6.5 (blue columns) shows that Participant 4 made his/her orders on his/her forecast in the Demand Visibility experiment; accordingly, Participant 2 made his/her production plans based on the forecast from the direct customer (Participant 4) in order to better fulfil the orders.

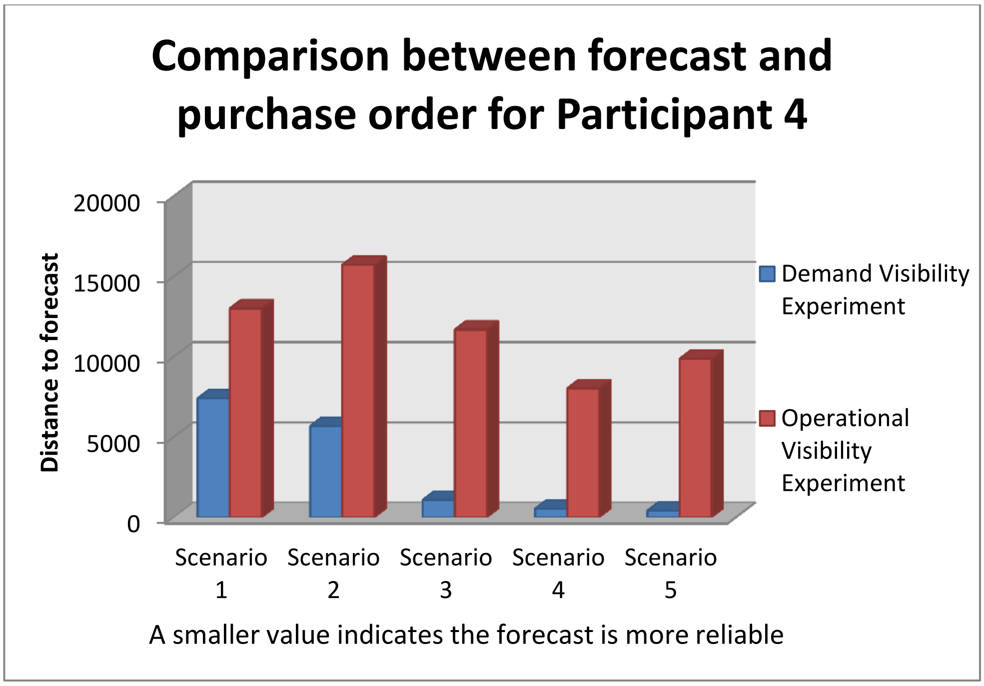


Figure 6.5: The comparison between forecast and purchase order for Participant 4 in Demand Visibility experiment and Operational Visibility experiment

In the Operational Visibility experiment, the red columns in Figure 6.5 shows the forecast from Participant 4 became unreliable since Participant 4 did not made purchasing orders based on his/her forecast, therefore, Participant 2 had to follow the central forecast. The reason for the unreliable forecast of Participant 4 may have been the increased supply chain uncertainties in the Operational Visibility experiment. When unexpected events happened, supply chain partners were most likely to mitigate their effect by amending their orders. These orders were not in line with their forecast. The centralised forecast, which is based on the end customer demand, was the only one which was not affected by unexpected events. Increasing visibility in operations helped them to ‘see’ the current situation such as real demand, current inventory, operation status, and the resulting decisions leading reduced supply chain uncertainty and optimisation of the supply chain performance.

Accurate and timely information sharing and frequent communication among supply chain partners are essential to build and maintain trust in supply chains (Handfield and Bechtel, 2002; Kwon and Suh, 2005; Khurana *et al.*, 2010). This research confirmed that increased visibility on inventory and customer demand enhances customer-supplier relationships. A study by Kwon and Suh (2005) suggested that information sharing lowers the supply chain uncertainty, which in turn improves trust among supply chain partners. The results from the Operational Visibility experiment indicate that sharing operational information further reduces supply chain uncertainty and enhances the level of trust. In addition, this research suggests that supply chain partners in the simulation supply chain developed stronger trust in the centralised forecast, rather than the forecast from their direct customers, and optimised the whole supply chain performance.

6.4 Supply chain visibility benefits

Sharing information in a controlled way brings competitive advantages to a supply chain. The previous section discussed the fact that sharing information reduces supply chain uncertainty and enhances the level of trust (Kwon and Suh, 2005; Khurana *et al.*, 2010). Studies from Li *et al.* (2001) and Dejonckheere *et al.* (2004) suggested that sharing information at a higher level helps to mitigate the bullwhip effect. Gavirneni *et al.* (1999) studied sharing information in a two-echelon supply chain, and found that sharing customer demand information reduced the inventory cost at both supplier and retailer levels. A simulation conducted by Disney and Towill (2003) indicated that the overall supply chain inventory and costs were reduced after sharing inventory information. A study by Wang and Wei (2007) indicated that information visibility (real time inventory and customer demand visibility) is critical for improving supply chain flexibility. Barratt and Oke (2007) concluded that high levels of information visibility brought sustainable competitive advantages to the simulation supply chain. The results from this simulation not only verify these findings, but, more importantly, demonstrate that supply chain visibility is an effective approach to improving supply chain LeAgility.

The major benefits of supply chain visibility in this simulation are:

1. Reduced the bullwhip effect:

   Results from the experiments show a 43.9% reduction of demand amplification after sharing inventory and customer demand; and a further 11.6% reduction after sharing operational information (Figure 5.1).

2. Improved forecast accuracy:

   Increased information visibility improves the supply partners' forecast accuracy (Figure 5.2).

3. Reduced inventory and cost:

   Results from the experiments indicate that the inventory level and cost of the simulation supply chain were reduced with the increased visibility level (Table 5.1 and Figure 5.5).

4. Improved customer service level:

   The customer satisfaction increases after sharing inventory, customer demand and operational information (Figure 5.6).

5. Improved planning and replenishment capabilities:

   Increased visibility on production schedule, capacity, raw material and finished goods inventory, work in process, forecast, and order status improves supply chain partners' planning and replenishment capabilities.

6. Improved suppliers' order fill rate:

   The backorders of the supply chain were reduced with the increased visibility level (Table 5.2).

7. Improved responsiveness and flexibility:

   Results from the simulation indicate that supply chain flexibility increases after enabling information visibility (Table 5.2).

The interaction between sharing real demand information and operational information and their benefits in this simulation are shown in Figure 6.6. The results of the Demand Visibility experiment show that sharing real demand information reduces the bullwhip effect, and improves forecast accuracy. Supply chain partners can then adjust their production plans and inventory policy synchronously, based on real customer demand data. As a result, total supply chain costs are reduced due to a decrease in inventory and overproduction; customer service level is also improved. Sharing operational information provides more information to support decision-making on inventory and production plans to further improve planning and replenishment; in addition, the early notice of supply chain disruptions helps improve the responsiveness and the flexibility of supply chain partners.

In summary, supply chain visibility is a concept built on **Plan** – **Monitor** – **Respond**. Sharing information helps supply chain executives to better **plan** their supply chain activities. **Monitoring** the pre-defined KPIs can help supply chain executives understand real time supply chain status and have prompt notice when the status changes. supply chain executives can then identify the issues and **respond** to it quickly. Achieving visibility in a supply chain can help synchronise activities and reduce lead time variability, leading to a better collaboration.

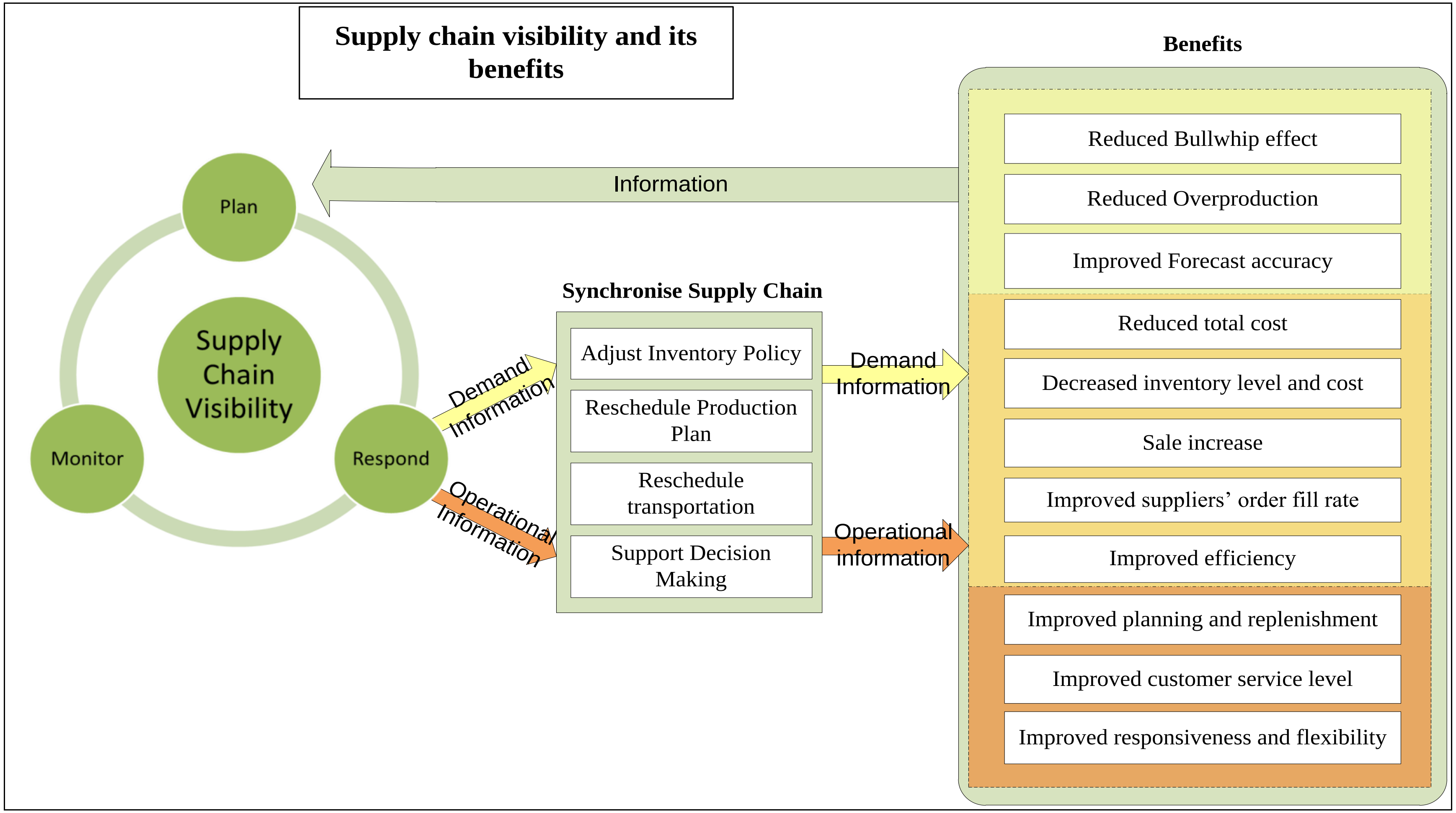


Figure 6.6: The interaction between supply chain visibility and its benefits

6.5 The impact of implementing visibility in the current business environment

The direct and indirect impacts of supply chain visibility on supply chain performance have been discussed; this section now explores the impacts of supply chain visibility on the two most recent discussed topics in supply chain management: economic fluctuation and major disruptions, such as that caused by the recent earthquake and tsunami in Japan.

6.5.1 Economic fluctuation

Economic fluctuation refers to unpredictable economic growth or depression over a short or long period. Since the 2008 Global Financial Crisis, companies have been under great pressure to cope with economic recession. As Gary Kilponen, Board Chair of the Supply Chain Council, once claimed: *supply chains have had to become more responsive to economic fluctuations as well as environmental and political disruptions in many ways* (Burnson, 2011). Preparation is everything, but how? Enabling visibility across the supply chain could be a good method of preparation. This section discusses the impact of implementing supply chain visibility on economic fluctuation.

The Inventory Cycle theory is generally agreed by many researchers to explain the cause of business cycles from the perspective of supply chain management (Flood and Lowe, 1995; Dimelis, 2001; Heng *et al.*, 2005). Blinder (1981) claimed that '*inventory fluctuations are important in business cycles… to a great extent, business cycles are inventory cycles*.' The Inventory Cycle theory described business cycles as three stages (Hall and Lieberman, 2007):

1. Stage one: during economic growth, companies are always short of inventory; therefore they increase the investment on expanding their capacities in order to catch the increasing demand.
2. Stage two: eventually companies hold plenty of inventories and start to reduce production orders and cut production schedule; this makes companies focus on cost reduction.
3. Stage three: the companies' spending decreases and recession start until inventory is reduced to a very low level.

A study by Heng *et al.* (2005) revealed a complex relationship between inventory investment and business cycle, and suggested that reduced inventory contributes to economic stability. This research confirms that enabling visibility across supply chains reduces the overall supply chain inventory. Thus enhanced visibility if widely applied, may be able to contribute to economic stability

The correlation between reduced inventory and economic fluctuations can be explained from the point of view of costs. Costs relating to inventory, in supply chain management, have been divided into four aspects: costs related to inventory itself, transportation costs, holding costs and administration costs (Garrison and Noreen, 2003). Enabling supply chain visibility in the simulation supply chain reduced costs relating to inventory and holding costs; and it could also in theory reduce administration costs for day-to-day operations. Reduced inventory costs can help companies to survive in an economic recession. For instance, in this simulation, supply chain partners held low levels of raw material and finished goods, and similar amount of inventory for work in process after enabling supply chain visibility; and administration costs would be reduced to a minimum due to the benefits of sharing information. Therefore, the overall costs relating to inventory would be reduced to a low level. When customer demand decreases in an economic downturn, raw material orders will be correspondingly lower. Since suppliers would hold a very low level of raw material and finished goods, the effect of the demand decrease would be limited. Thus, enabling supply chain visibility could reduce the effect of economic fluctuations.

The contribution of supply chain visibility to economic stability could also be explained by using the Under Consumption/Over Production theory. This theory suggests that an economy eventually produces more products or services than customers can consume; an economic downturn happens when production and prices drop to the point that the productions exceed the customer demand; otherwise, a growth starts (Hall and Lieberman, 2007). The results from the simulation suggest that overproduction in the simulation supply chain was reduced with increased supply chain visibility. Reduced overproduction would help maintain prices and profitability by better matching supply and demand.

6.5.2 Supply chain risk management after Japan's earthquake and tsunami

The highly integrated global supply chain has brought numerous benefits in terms of improved productivity and efficiency. However, the recent earthquake and tsunami in Japan exposed the serious vulnerability of today's global supply chains. Many worldwide manufacturers had to grind to a halt due to the stoppage of their sole suppliers in Japan. This should remind supply chain executives to review their supply chain risk management in order to better cope with disruptions. This research contributes to supply chain risk management (SCRM) in three aspects:

6.52.1 The bullwhip effect and demand variability

Enabling supply chain visibility mitigates the impact of the bullwhip effect and demand variability. Christopher and Lee (2004) believed that lack of confidence among supply chain partners is a cause of supply chain risks. They suggested that one key element to mitigating supply chain risk is improving information visibility amongst supply chain partners. Giannakis and MichalisLouis (2011) developed a multi-agent SCRM model and demonstrated the advantage of this model over traditional ICT-based SCRM models, in terms of mitigated risk of demand turbulence and reduced the probability of disruptions occurring through improved information sharing. The results of this research support their works.

6.5.2.2 Supply chain disruptions

Improved supply chain visibility mitigates the risks of supply chain disruptions by improved flexibility. Previous research has suggested that companies can reduce the risk of supply chain disruptions by improving flexibility through implementing contingency planning (Fredericks, 2005; Skipper and Hanna, 2009). The results from Skipper and Hanna's (2009) study showed a positive effect on a company's flexibility, which in turn reduced risk exposure caused by supply chain disruptions for both the individual and the entire supply chain. Tang and Tomlin (2009) argued that it is not clear how much flexibility is required for a company to reduce supply chain risk, although the benefits of flexibility for mitigating supply chain risk have been well discussed. They explored the capacity of flexibility level for reducing three types of risks: supply, process and demand, and concluded that a company only needed a limited level of flexibility to mitigate these three types of supply chain risks. This research suggests that enabling operational visibility enhances the flexibility of the supply chain, which in turn reduces the impact of supply chain disruptions.

6.5.2.3 Single or multiple sourcing decision-makings

Supply chain visibility facilitates single or multiple sourcing decision-making. The debate between single and dual sourcing has become increasingly popular after Japan's earthquake and tsunami. From the point of view of risk mitigation, multiple sourcing (diversification) is advisable in order to mitigate supply chain risks (Blome and Henke, 2009; Yu *et al.*, 2009; Wang *et al.*, 2010b; Whitney *et al.*, 2011). In reality, many companies still persist in purchasing certain components from a single, even solo supplier. They believe the benefits of developing a long-term relationship and adopting a temporary diversification recovery strategy outweigh some obvious short-term risks (Whitney *et al.*, 2011). In addition, Sheffi (2007) noted that multiple sourcing increases the operational complexity and costs, and limits trust building and relationship development with suppliers. However, Yu *et al.* (2009) found that both single sourcing and multiple sourcing can be effective, depending on the probability of disruptions occurring.

Blome and Henke (2009) also suggested that making single or multiple sourcing decisions is very much dependant on the specific situation: its probability of risk occurrence and the outcome of risk occurrence. Figure 6.8 shows the matrix for single sourcing or multiple sourcing decision-making. The probability of risk occurrence for single sourcing is smaller; however, the potential impact of a disruption is more severe since no alternative suppliers are available in short period of time. On the contrary, the probability of risk occurrence for multiple sourcing is higher since the increased supplier base improves supply chain complexity; but by doing so, the potential damage caused by a disruption will decrease. Increasing supply chain visibility may not be able to predict or avoid a disruption; however, it can minimise the damage caused by the disruption.

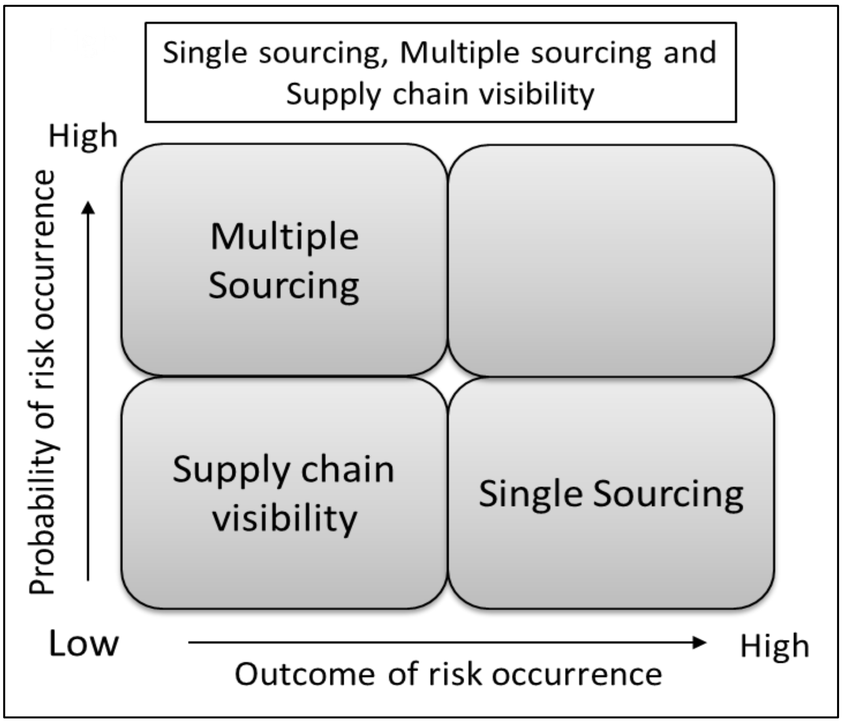


Figure 6.7: The matrix for single sourcing or multiple sourcing decision-making

6.6 Comments from the Journal of Operations Management

The simulation devised in this research had two versions: Simulation Version One and Two. A paper was generated for the Journal of Operations Management according to the results from the Simulation Version One (Appendix 5). In this simulation, two experiments with different information configurations were examined to explore the effects of demand visibility and operational visibility. The supply chain performance was measured in terms of stock level (leanness) and customer service level (agility). The paper was declined because it did not fit the scope of the journal and detailed descriptions about simulation design and research methodology were missing. However, the reviewers of the Journal of Operations Management believed the paper was interesting and valid, and made some good feedbacks and comments. For example, most of the comments were related to simulation design because of insufficient descriptions on simulation design such as supply chain selection, information sharing structure, participant selection, and simulation development. Their comments and feedbacks were carefully evaluated to improve the simulation design of this research. This presented work is based on the results from the improved simulation, the Simulation Version Two.

6.7 Data reliability

Several methods are used to improve the reliability of the simulation:

1. The simulation is tested first to examine its reliability.
2. The selected participants have a similar level of knowledge on supply chain management.
3. The variables can be controlled. For example, the simulation has the standardised forecasting method and inventory management policy to mitigate the impact of nonsense decisions on supply chain performance.
4. The experiment stops when an error occurs, and starts from the beginning of the current round in order to avoid the impact of unnecessary mistakes on supply chain performance.
5. The simulation scenario used in this research has been applied twice by two different groups of participants (Simulation Version One and Two). Table 6.2 shows the difference between the two simulations. The similar

results from both simulations indicate a good reliability of the simulation. Appendix 5 shows the results from Simulation Version One.

Table 6.2: The difference between Simulation Version One and Two

	Simulation Version One	Simulation Version Two
Rounds of each scenario	12	16
Number of experiments	2 Demand and Operational Visibility experiments	3 Demand and Operational Visibility experiments + Decoupling point and postponement experiment
Scenarios for each experiment	4	5 (one for lower information sharing frequency)
Performance measurement	The bullwhip effect, LeAgilty	The bullwhip effect, LeAgility, Human behaviours
Results	Reduced inventory level, improved customer satisfaction, improved overall supply chain LeAgility	Reduced inventory level and costs, improved customer satisfaction and flexibility, improved supply chain LeAgility, and enhanced trust

6.8 Evaluation

The supply chain visibility concept described in this work has been adopted in two practical cases in order to evaluate its business implications. One is a visibility module for the West Midlands Collaborative Commerce Marketplace (WMCCM). The simulation support IT system used in this research was conceptually based on the WMCCM system. The other is the IMAGINE (Innovative End-to-end Management of Dynamic Manufacturing Networks) EU Framework Seven, Factory of the Future project where achieving end-to-end product lifecycle visibility is the cornerstone of the research.

6.8.1 Case One – the visibility module on WMCCM

The conceptual system described in this paper has been implemented in the West Midlands Collaborative Commerce Marketplace (WMCCM, www.wmccm.co.uk). This is a business ecosystem, with over 10,000 SME members, which can quickly breed demand driven virtual organisations to target opportunities based on the competences of member organisations rather than their product or services. WMCCM imports e-tenders from public and private sources. Tenders are automatically analysed and classified according to their capability requirements. The partner search function matches the tenders and competence descriptions in user profiles to suggest an initial best-fit grouping of SMEs who between them have the competencies to bid for that tender contract. This is intended to be led by the best qualified partner, who builds virtual organisation with the help from a WMCCM broker if required. Each virtual organisation has a secure online collaboration project space to design their product or service and manage their supply chain using a supply chain visibility module. This module allows the user to monitor their products or services after setting appropriate KPIs, and to track and trace the individual components through a user defined identity code. A 'traffic light' dashboard shows a green, amber and red graphic view of supply chain performance according to the status of their KPIs. A notification function alerts the users when the amber or red status appears.

A visibility solution for the HP case study using the WMCCM Visibility Module is illustrated in Figure 6.9. Green and red colours present the status of KPIs. The users need to adjust their processes based on the updated information, if the KPIs status becomes red. The WMCCM functionality will be used to assess within a real environment if the conclusions drawn from the experiments undertaken are widely valid.

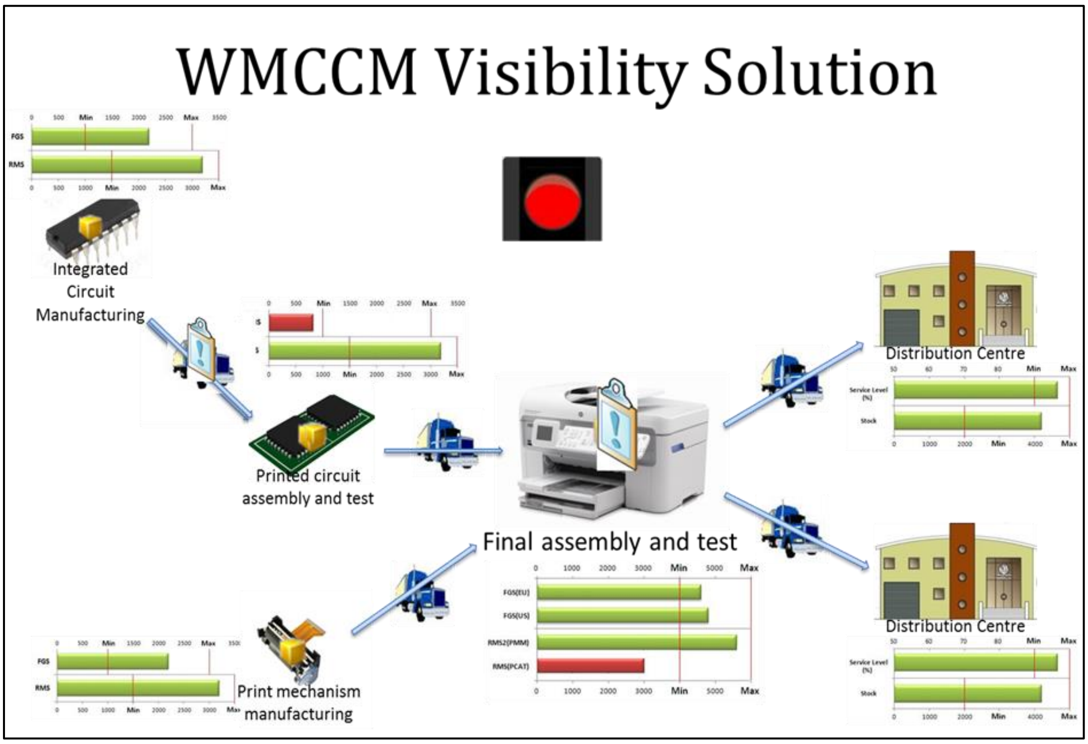


Figure 6.8: WMCCM Visibility Module Solution

6.8.2 Case Two – The EU IMAGINE Project

The IMAGINE Project (www.imagine-futurefactory.eu) is funded by the European Commission under the 'Virtual Factories and Enterprises' theme of the 7th Framework Program (FoF-ICT-2011.7.3, Grant Agreement No: 285132). It focuses on designing and developing a novel comprehensive solution and user-friendly framework for end-to-end dynamic manufacturing networks management by providing a virtual collaboration platform for the manufacturing network and its global partners to view and integrate their manufacturing-related sources, and to enable service-enhanced product and responsive manufacturing processes through the value chain.

Achieving end-to-end visibility across the dynamic manufacturing network (DMN) is the foundation of the success of the IMAGINE project. Therefore, it links and optimises the data and process information from two disparate management systems: Enterprise Resource Planning (ERP/MRP) and Manufacturing Execution Systems (MES). Figure 6.10 illustrates the IMAGINE Management and Monitoring framework. Its basic components are a DMN management lifecycle and ICT-based supporting platform. The various blueprint modules provide the necessary information and essential knowledge to support a DMN lifecycle (network configuration – manufacturing design – monitoring and governance of manufacturing network). A manufacturing blueprint repository and partner blueprint repository allow the manufacturer to quickly configure its production processes and its partners according to customer orders. The end-to-end manufacturing design suite enables the impact of various decisions such as upgrading production and changing partners to be reviewed and simulated. Once the production is ready to launch, the quality assurance blueprint will be introduced to measure and monitor the performance of processes according to the Key Performance Indicators (KPIs) specified in the network configuration. It also notices the alerts to status changes and disruptions in order to respond in a timely manner. A range of user-friendly display options, such as dashboard, chart and graphic, are offered in order to enable smart decision-makings.

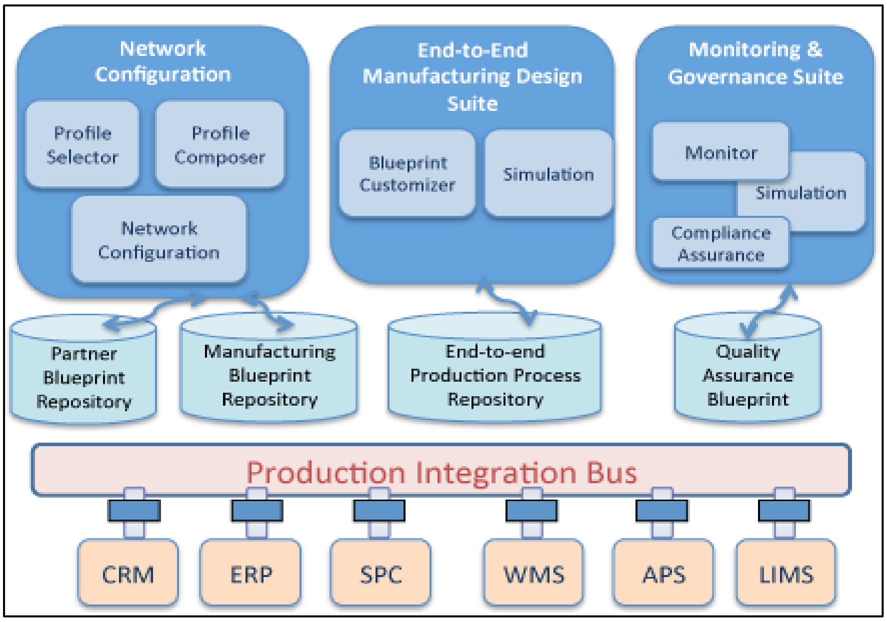


Figure 6.9: the IMAGINE Management and Monitoring framework (Source: Adapted from IMAGINE (2012))

An example of implementing the IMAGINE method in a bike factory. The bike factory receives an order from customers and provides a draft specification to its external partners. Then, the external partners work out detailed blueprints for each component, and collaborate to develop the final product. The IMAGINE platform automatically indicates the capacity and capability of every member of the dynamic manufacturing network and suggests a list of suppliers, according to the specifications of the final product. The bike factory reviews the suggested suppliers and sends orders to the appropriate suppliers and awaits delivery. The processes and order status can be viewed in a dashboard on the IMAGINE platform. This platform automatically sends an alert when disruptions occur or when there are status changes based on the defined KPIs. Once an alert is received, the factory can respond to the disruption quickly and select an alternative supplier which is capable of carrying on the remaining orders. Finally, the order is delivered to the customer in a timely and cost effective manner, with the correct qualifications.

6.9 Research limitations

This research uses a hybrid simulation and a low-cost Google based application as the research method to investigate the impact of supply chain visibility on supply chain LeAgility. However, this is not the only research method that could be used in this research area. There are many other methods and technologies available which may respond differently to visibility. This section discusses the limitations of this research.

6.9.1 Visibility and supply chain type

The simulation was designed based on a typical four-echelon supply chain often discussed in literature. The results show the impact of increased visibility on improved supply chain LeAgility. However, what would the result have been if it were implementing visibility to other types of supply chain? For example: would the visibility still be effective in a simple supply chain? Or what would the result be in a complex supply chain? As discussed, choosing an appropriate visibility level depends on supply chain uncertainties. The impact of visibility on a simple supply chain may be not obvious. For a long and complex supply chain, the impact of visibility on performance improvement cannot be neglected. This may be explained from the perspective of information flow: the information takes longer to flow in a complex supply chain, and the delayed information flow increases supply chain uncertainty. As a result, the more complex a supply chain, the more necessary it is to implement visibility. In order to fully validate this result, other types of supply chain structure need to be assessed.

6.9.2 The impact of profit visibility

This research focused on measuring the four types of visibility proposed by Camerinelli (2005): Product Visibility, Process Visibility, Partner Visibility and Profit Visibility. However, the financial settings for measuring Profit Visibility in this research are normal, such as profit and a weekly report. Other key financial indicators, which measure the impact of supply chain actions on profit, may respond differently to increased visibility.

The author believes that achieving profit visibility in the simulation helps supply chain partners to identify the key financial drivers in their relationships with others. Sharing information about these financial drivers is very useful in developing relationships and building trust. Supply chain partners could then maintain their relationships in a much better and smarter way by creating a personalised performance measurement platform, based on these shared key financial drivers.

6.9.3 Other technologies

"*The medium is the message*." --- McLuhan (1964)

Environmental uncertainty in a supply chain can be classified into three categories: customer uncertainty, supplier uncertainty, and technology uncertainty (Li and Lin, 2006). This research has considered customer and supplier uncertainty through demand and operational visibility; however, the effect of different technologies on achieving the visibility of a supply chain needs to be explored.

For example, if a supply chain partner achieves visibility through the RFID; will the results still be similar? Will a low cost 'cloud' applications lead to a better collaboration in a virtual supply chain network? Will trust be increased if web cameras are used to show live the key processes in the supply chain network? One local engineering SME has installed web cams on their machines so that their main customers can login and see their orders being processed. This facility has caused a huge increase in enquiries from around the world for the services of this SME. How effective would it be to use social media platforms like Facebook or Twitter in achieving visibility in a supply chain?

Advancing technology may continuously decrease the cost of sharing information, and make visibility in supply chains a common reality. The main issue for supply chain executives is how to achieve information visibility by aligning appropriate technologies with their business models.

7

Conclusions and Future Work

7.1 Conclusions

This research used a simulation to evaluate the effect of supply chain visibility on improved LeAgile supply chain performance, by examining different information sharing configurations in a typical four- echelon supply chain. It has demonstrated that enabling supply chain visibility plays a vital role in improving supply chain LeAgility. Although previous research in the literature has provided many approaches for combining the benefits of the lean and agile paradigms, the results from this research indicate that the supply chain visibility approach has advantages over those approaches for improving supply chain LeAgility. Therefore, the conclusions drawn from this research are:

1. This research evaluated the decoupling point and postponement approaches and demonstrated that supply chain visibility can be a lower cost, more effective approach for improving supply chain LeAgility. The results obtained show that after increasing visibility the overall supply chain performance increased by 26.3% and 26.4%, compared to the decoupling point and postponement approaches.
2. This research also addressed the gap of previous research on supply chain visibility by exploring the correlation between increased visibility and improved supply chain performance. The results from this research show a significant correlation in improved supply chain LeAgility with the degree of visibility, but this is not a linear relationship (see Chapter 6.1). Sharing more information at higher frequency will make the supply chain more visible, however it does not necessarily mean a better supply chain

performance. The author identified two key elements of the supply chain visibility to explain this phenomenon: the content of shared information and information sharing frequency. Figure 6.1 suggests that there is a 'critical' information sharing frequency for each supply chain. This frequency depends on the lead time and uncertainty of a supply chain. Sharing information at the 'critical' frequency will lead the supply chain to its most LeAgility; if higher than 'critical' frequency, the supply chain will be more visible, but suffer extra resource expenses; an information rate below 'critical' will reduce decision making quality and resulting the performance. However, the results from the Operational Visibility Experiment suggest that shared information content is more important than information sharing frequency. Sharing the right information at a lower frequency is better than more information at a higher frequency – maybe because people are unable to process it into decision making and hence it incorporates more digital waste.

3. This research differs to previous research on the bullwhip effect. It examined the effect of increasing visibility on demand and operational information on the bullwhip effect in a four-echelon supply chain. The results show a 43.9% reduction in demand amplification after sharing inventory and customer demand; and a further 11.6% reduction after sharing operational information.
4. The results from this research suggest a complex relationship between trust and visibility. The results from the Demand Visibility experiment indicate that the increased visibility on inventory and customer demand enhances customer-supplier relationships. The results from the

Operational Visibility experiment suggest that sharing operational information can reduce supply chain uncertainty and enhance the level of trust.

7.2 Future work

Future research should focus on addressing the research limitations discussed in chapter 6.10:

1. This research was based on a typical four-echelon supply chain, the generalisability of the results to other supply chain architectures needs to be explored.
2. This research investigated the effect of visibility through a cloud based solution; the contribution of other technologies on achieving supply chain visibility needs to be explored.

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Appendix 1

The Customer Demand

The customer demand was generated based on the demand pattern of the history of sales data of the HP case study. Individual orders were generated randomly within the overall demand pattern in order to examine how well the supply chain responded to a fast changing environment. Table 1 below lists the detailed customer demand for each product. The simulation used the same demand data for all experiments in order to compare the results from different scenarios. The participants changed their roles in each scenario to reduce the possible impact of memorising the demand data and thus minimising the impact of the 'learning effect' on the supply chain performance.

The customer demand can also be viewed in a graph (Figure 1). It shows that the customer demand of Product A for both US market and Europe market are fluctuant and unpredictable; on the contract, the customer demand of Product B is less unpredictable.

Table 1: the customer demand for each production

	US Market		Europe Market	
Week	AU	BU	AE	BE
1	12459	4898	18999	7498
2	15731	2503	24119	6043
3	18569	2978	21489	8601
4	13024	2445	22145	6409
5	21245	3572	25483	6448
6	18793	3265	17997	5678
7	13986	3483	15968	7458
8	13412	4310	17844	7368
9	22341	2951	18988	8065
10	18790	3708	30649	5731
11	20987	4264	26539	8904
12	22045	4703	26075	8247

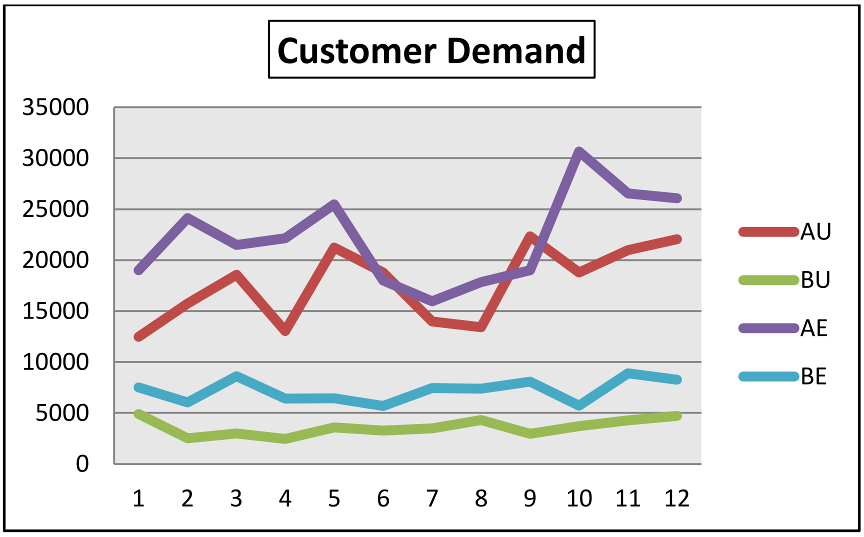

Figure 1: The real customer demand for each product

Appendix 2

Forecasting

A good supply chain performance depends on an accurate forecast, therefore, all the forecasts were required to update each week in response to new demand data. In the simulation the participants had to change their role for each scenario, so the centralised forecasts generated by distribution centres were changeable. A slight difference in forecast may greatly influence the final supply chain performance. In order to investigate the impact of visibility on supply chain performance, the forecast accuracy had to be maintained at a reasonable level. Therefore, the participants adopt the same forecasting method – moving average to make their forecasts. Equation 1 calculates the moving average of forecast over the last N weeks ending in Week t.

$$f_t = \frac{S_{t-N+1}+S_{t-N+2}+S_{t-N+3}\pm\cdots+S_{t-1}+S_t}{N} \qquad (1)$$

S: forecast

N: in the last N weeks

t: Week number

The following describes how to make a forecast for Participant 5 by adopting the moving average method. The forecast made by Participant 5 through Equation 1 is shown in Table 1.

Table 1: The forecast of Participant 5

Week	Demand	Forecast	
	15780	15780	
	21046	21046	
	13402	13402	
	12030	12030	
1	12459	15564.5	=(15780+21046+13402+12030)/4
2	15731	14734.25	=(21046+13402+12030+12459)/4
3	…	13405.5	=(13402+12030+12459+15731)/4
4		…	…
5			
6			

Appendix 3

Unexpected events

The simulation used three variables to simulate the supply chain uncertainties. They are defect rate, late delivery and machine breakdown which correspond to the three types of supply chain uncertain defined by Gaonkar and Viswanadam (2007): Deviation, Disruption and Disaster. The unexpected events were generated randomly in the first scenario and fixed for rest of scenarios. Table 1 and 2 recorded all the unexpected events of Experiment Two (Operational Visibility) and Three (Decoupling point and Postponement).

Table 1: The unexpected events for Operational Visibility experiment

	Defect Rate (%)				Late Delivery (Days)				Machine Breakdown			
week	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
1	0.76				0				No			
2	1	1.2	1.09		0	0	0		No	No	No	
3	1.16	0.75	0.85	1.11	0	0	**5**	0	No	No	No	No
4	0.56	1.01	0.66	0.81	**4**	0	0	0	No	No	No	No
5	1.25	1.34	1.43	0.58	0	0	0	0	No	**Yes**	No	No
6	1.34	0.68	1.13	1.46	0	0	0	0	No	No	No	No
7	1.16	1.39	1.32	1.12	0	0	0	0	No	No	No	No
8	0.6	0.72	0.85	0.83	0	0	0	**2**	No	No	No	No
9	1.04	1.26	0.86	1	0	0	0	0	No	No	No	No
10	1.1	0.59	1.47	0.59	**1**	0	**3**	0	No	No	No	No
11	1.1	1.27	1.13	1.2	0	0	0	0	No	No	**Yes**	No
12	1.35	0.88	0.7	0.52	0	**2**	0	**4**	No	No	No	No
13		1.4	0.55	1.28		0	0	0		No	No	No
14				1.29				0				No

Table 2: The unexpected events for Decoupling point and Postponement experiment

	Defect Rate (%)						Late Delivery (Days)						Machine Breakdown					
week	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
1	0.76						0						No					
2	1	1.2	1.09				0	0	0				No	No	No			
3	1.16	0.75	0.85	1.11			0	0	**5**	0			No	No	No	No		
4	0.56	1.01	0.66	0.81	0.73	0.94	**4**	0	0	0	0	0	No	No	No	No	No	No
5	1.25	1.34	1.43	0.58	1.02	0.68	0	0	0	0	0	0	No	**Yes**	No	No	No	No
6	1.34	0.68	1.13	1.46	0.94	1.5	0	0	0	0	0	0	No	No	No	No	No	No
7	1.16	1.39	1.32	1.12	0.65	0.85	0	0	0	0	0	0	No	No	No	No	No	No
8	0.6	0.72	0.85	0.83	1.43	0.7	0	0	0	**2**	0	0	No	No	No	No	No	No
9	1.04	1.26	0.86	1	0.9	1.17	0	0	0	0	0	0	No	No	No	No	No	No
10	1.1	0.59	1.47	0.59	0.65	0.68	**1**	0	**3**	0	0	0	No	No	No	No	No	No
11	1.1	1.27	1.13	1.2	1.42	0.8	0	0	0	0	0	0	No	No	**Yes**	No	No	No
12	1.35	0.88	0.7	0.52	1.24	1.24	0	**2**	0	**4**	0	0	No	No	No	No	No	No
13		1.4	0.55	1.28	1.13	1.35		0	0	0	0	0		No	No	No	No	No
14				1.29	1.29	1.17				0	0	0				No	No	No
15					1.19	1.24					0	0					No	No

Appendix 4

Weekly report

In the simulation, weekly reports were provided for all participants. These reports show the weekly total costs. The participants can adjust their strategies to reduce their costs according to the information in the reports. Table 1 illustrates a weekly report for Participant 3 in week 7.

Table 1: An example of weekly report

Week	**7**				
Product	A3		B3		Note
Fixed Cost				**5000**	the fixed cost for each week is £5000
Raw Material					
RM Ordered		20000		13000	
RM Brought Fwd		0		0	
RM Received		20000		13000	
Total RM before Production		20000		13000	
Used in Production					
RM Stock After Production		0		0	
Total RM Cost		0		0	RM stock cost is £5% of RM stock
Manufacturing					
Production plan		20000		13000	
Manufacturing Cost		2000		1300	Manufacturing cost is 10% of the production
Output	19890		12928		
Scrap Rate		0.55		0.55	
Total Manufacturing Cost		2000		1300	
Shift Cost	1			500	£500 each shift
Late delivery/Breakdown	No			0	late delivery + machine breakdown
Total operation cost				**3800**	
Finished Goods					
Order/Demand	49000		11000		
Delivery/Sold	49000		11000		
Delivery Cost		2450		550	Delivery cost is £5% of the delivery
FG Stock	2703		2156		
FG stock cost		135.15		107.8	FG stock cost is £5 % of FG inventory
Total FG Cost		2585.2		657.8	Total cost of FG stock cost + delivery cost
Penalty		0		0	The penalty is £1 per backorder
Total Cost		**4585.2**		**1957.8**	Total cost of Product A and B
Overall Cost				**12043**	Overall cost

Appendix 5

Simulation Version One

Simulation Version One included two experiments: Demand Visibility and Operational Visibility experiments. The results were measured in terms of total supply chain inventory (Leanness) and overall customer service level (Agility). A total value for the supply chain was then calculated to reflect the optimization enabled (see Chapter 4.6, Equation 5). The higher the value, the better the overall supply chain performance achieved.

1. Demand Visibility experiment

1.1 Scenario configuration

In this scenario, the supply chain operated as in a planned business environment; there were no unexpected events. This scenario assesses supply chain performance against increasing levels of information sharing. Table 1 shows the four levels of visibility applied.

Table 1: Levels of Visibility for Demand Visibility experiment

Visibility Level	Share Forecast	Share Real Demand	Share Inventory	Information share structure
No Visibility	×	×	×	Sequential (in one direction)
Half Visibility	√	×	×	Reciprocal (Two-way, multiple Partners)
Partial Visibility	√	√	×	Reciprocal (Two-way, multiple Partners)
Full Visibility	√	√	√	Hub-and-spoke (Two-way, Centralized)

1.2 The results from the Demand Visibility experiment

Figure 1 illustrates the effect of improved SCV on the bullwhip effect, order fluctuations decreased with an increase in the SCV level. Although, there is considerable variance between the 2nd Tier suppliers' orders with the others in 'half visibility', the levelling of orders are better in 'half visibility' than in 'no visibility'. With a further increase in SCV level ('partial' and 'full visibility') better damping of the bullwhip effect is achieved.

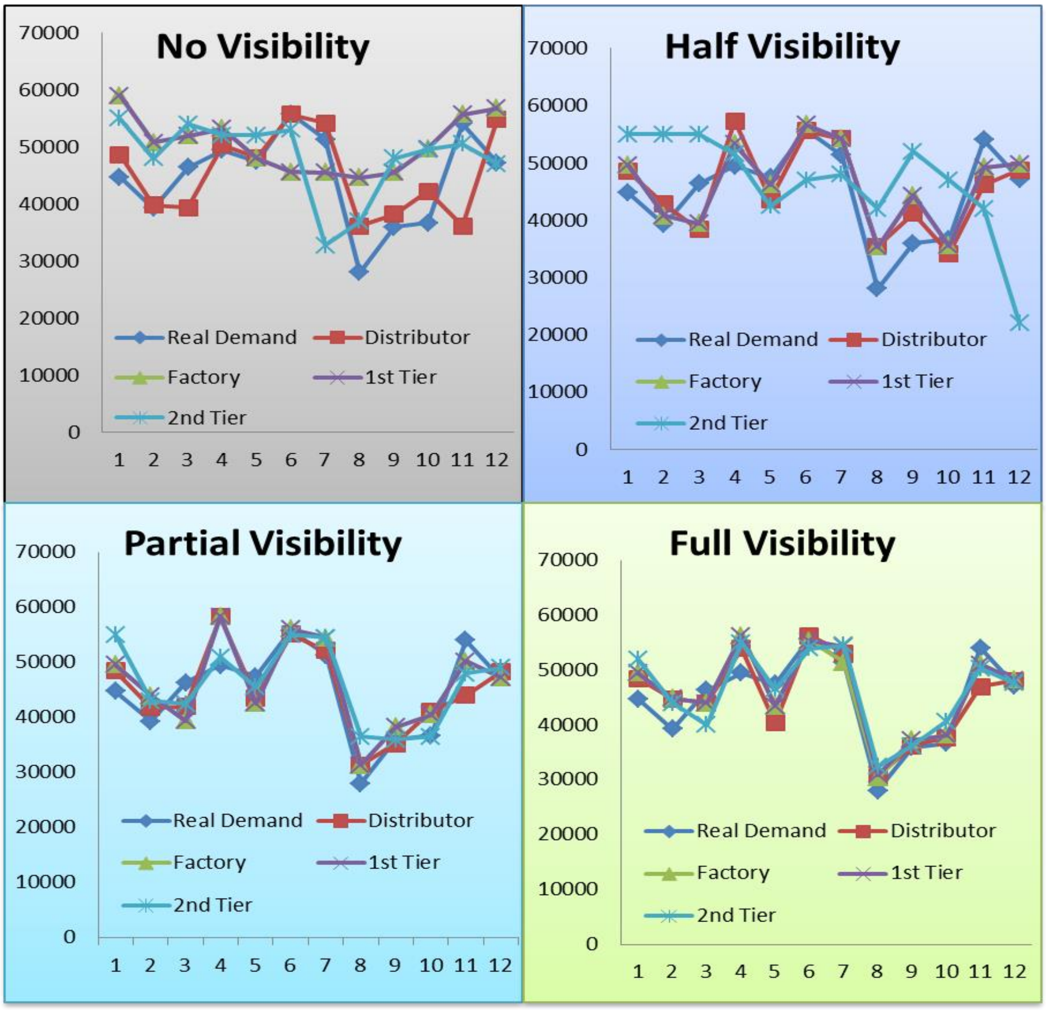

Figure 1: The bullwhip effects in the Demand Visibility experiment

The overall inventory level and customer service level for the supply chain in the Demand Visibility experiment are illustrated in Figure 2. It shows a clear correlation between increasing visibility levels resulting in decreasing inventory for the supply chain configuration used. The relationship with customer service shows a strong correlation until visibility level 3 (partial visibility) and slight decrease on then moving to full visibility.

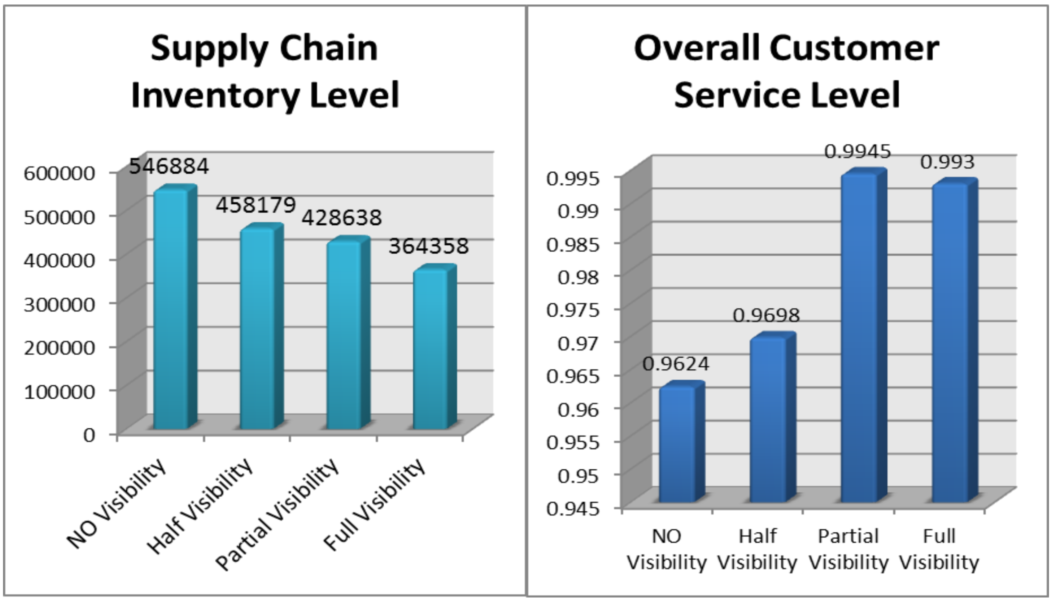

Figure 2: Total supply chain inventory and overall customer service level for the Demand Visibility experiment

The total supply chain value (as calculated by Equation 5) for the four levels of visibility in the Demand Visibility experiment is shown in Figure 3. It clearly shows the total value increasing with the improved visibility level. Table 2 lists the performance of individual participants and their performance change with different visibility levels. Most of the participants can achieve LeAgility (lower cost level with increased customer service level) with increased visibility; Except for Participant 4 and 5. However, the entire supply chain achieved the best performance in full visibility with lowest cost and highest customer service level.

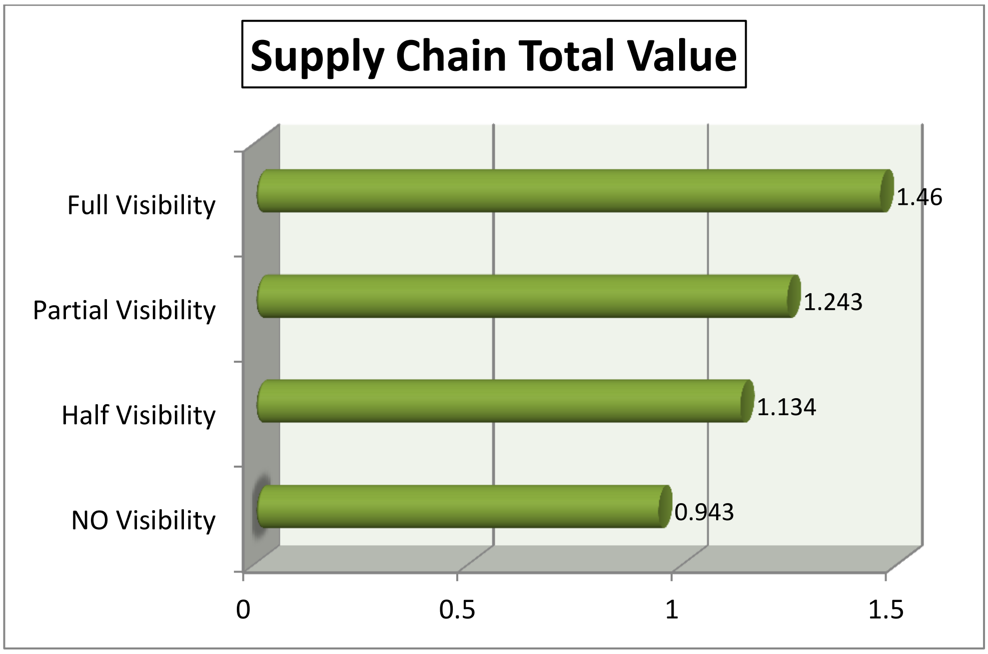

Figure 3: Supply chain total value of Simulation One

Table 2: Summary of individual performance for the Demand Visibility experiment

Participants	**No Visibility**	**Half Visibility**	**Partial Visibility**	**Full Visibility**
IC MFG(P1)	—	Cost ↓ Service ↓	Cost ↓	LeAgile
PCAT (P2)	—	Cost ↓	Cost ↓	LeAgile
Print Mech (P3)	—	Cost		LeAgile
FAT (P4)	Agile	Lean	Service ↓	Service ↓
US DC (P5)	—	Service ↓	LeAgile	LeAgile
EU DC (P6)	—	Cost ↓ Service ↓	Cost ↓	LeAgile

2. Operational Visibility experiment

2.1 Scenario configuration

This Simulation explores the effect of access to the current operational situation of each actor by the other actors. With increased visibility, supply chain executives can respond to changing situations with more confidence and accuracy. This scenario introduced four common types of unplanned problems; they are the increased scrape rate, late delivery, machine breakdown, and significant demand change. Table 3 shows the different aspects of visibility enabled in Simulation two.

Table 3: Levels of Visibility for the Operational Visibility experiment

Visibility Level	Share Forecast	Share Real Demand	Share Inventory	Unexpected events	Information Share Structure
No Visibility	√	√	×	×	Sequential (in one direction)
Half Visibility	√	√	√	√	Reciprocal (Two-way, multiple Partners)
Full Visibility	√	√	√	√	Hub-and-spoke (Two-way, Centralized)

2.2 The results from the Operational Visibility experiment

The overall inventory level and customer service level for the supply chain in experiment two are presented in Figure 4. It shows that the overall customer service level increased with the increased visibility. However, the supply chain held more inventories with half visibility than with no visibility, but inventory reduced with full visibility. It appears that knowledge of unexpected events possibly occurring forced the participants to reconsider their strategy. This resulted in more inventory to satisfy service level goals as a result of the actors only being able to see one step up or down the chain, but when they were able to see the whole system status, they had longer to react and where able to optimize better for fluctuations and decrease the overall inventory.

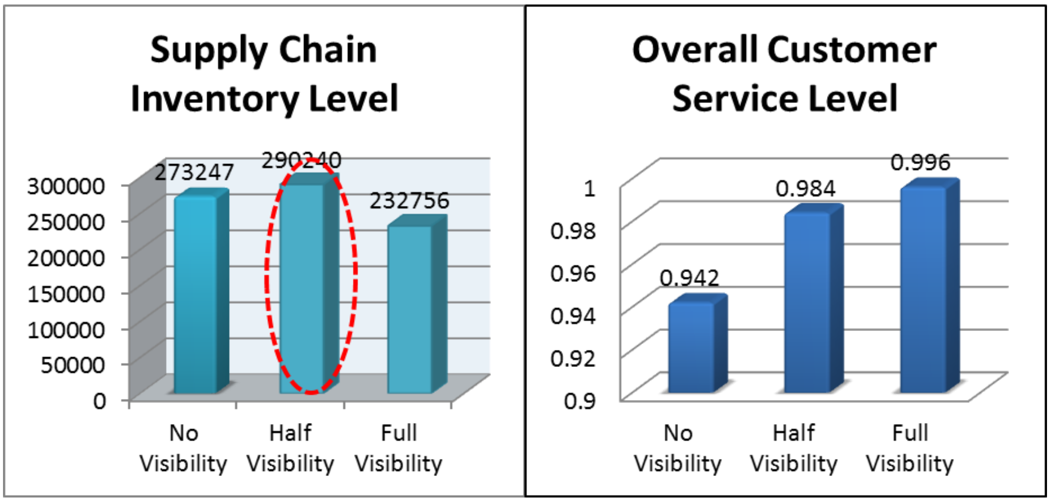

Figure 4: Total supply chain inventory and overall customer service level for Operational Visibility experiment

The total supply chain value for the different levels of visibility in Simulation two are shown in Figure 5. The entire supply chain had best performance in the full visibility situation. The no visibility level and half visibility had similar levels of performance. Table 4 shows the performance of cost and service level for individual participants. Apart from Participant 2 and 5, the rest of participants achieve LeAgility (lower cost level, but increase customer service level) with increased visibility.

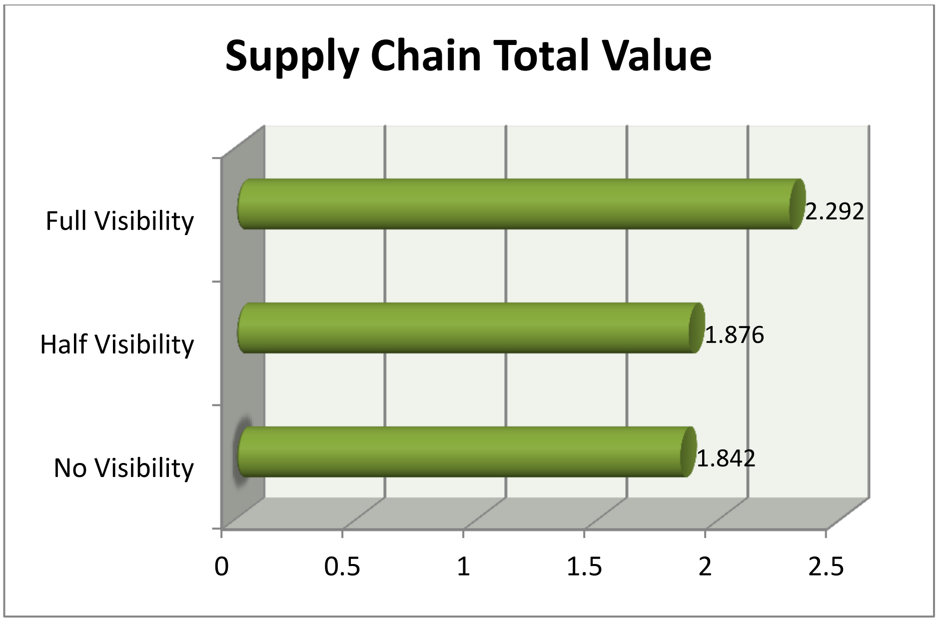

Figure 5: Supply Chain Total Value for Operational Visibility experiment

Table 4: Summary of individual performance for the Operational Visibility experiment

Participant	**No Visibility**	**Half Visibility**	**Full Visibility**
IC MFG(P1)	—	Cost↓	LeAgile
PCAT (P2)	Lean	Cost↓	Agile
Print Mech (P3)	—	Cost↓	LeAgile
FAT (P4)	—	Cost↓	LeAgile
US DC (P5)	—	LeAgile	Cost↓
EU DC (P6)	—	Cost↓	LeAgile

3. Discussion

In the simulations, with increased visibility in the supply chain, the participant improved the overall supply chain performance by reducing the total cost of supply chain and increasing the customer service level. Table 2 and 4 indicated that most but not all the participant achieved their best LeAgility (Lowest cost and highest service level) while the entire supply chain had the highest total value in full visibility.

With the enhancement of visibility across the supply chain, where timely and accurate information concerning supply chain performance are available for all supply chain members, a LeAgile supply chain can be achieved. Visibility mitigates the bullwhip effect (Figure 1). The total excess inventory in full visibility reduced by 33.4% compared with the no visibility level. Through sharing demand and operational information across the supply chain, the participant can ‘see’ the status of entire supply chain and better respond to any deviations.

The increased visibility of demand encourages the supply chain partners to merge their individual strategies from multiple forecasts to centralized demand driven (See Figure 1). The authors believed that the value of centralized forecast information was recognized only when the access to real customer demand data was made available. This data helped to verify the validity of centralized demand and merge the individual forecasts to a centralized demand driven.

Table 2 in Simulation One and Table 4 in Simulation Two indicated that the entire supply chain achieved the best LeAgility with full visibility, but not all the supply chain members had their best performance. This may be because the increased visibility of supply chain enables the supply chain partners to access each other's operational status and encourages them to make decisions that are more optimal for the whole system, rather than just themselves. Supply chain executives have to better balance the interests of each individual member and the supply chain as a whole. This demonstrates the truth that sometimes for a system, some sub systems may have to lose, for the whole system to gain. Without visibility these tradeoffs are often not clear and sub optimal performance occurs because the overall benefits are not clearly visible to all participants.

There is some unexpected behaviour with inventory management in Simulation Two (Figure 4). In the half visibility level, the entire supply chain hold much more inventory than with NO Visibility. A reason for this may be the 'learning' effect among participants. They learned from the No Visibility Scenario and changed their strategies by holding more inventories to avoid the large back orders. Another reason for this may be a lack of value in the information provided. So called 'digital waste' (Abbott et al., 2005, p.17). Digital waste can complicate and confuse decision-making. Thus, centralized demand information sharing but without real customer demand information may be seen as the digital waste that hampers individual decision making processes.

In summary, the results from the simulation demonstrated that increasing information visibility through a supply chain has positive effect on improved supply chain LeAgility in terms of total inventory reduction and improved customer service level.

Appendix 6

Data Analyse*

*Data analyse is stored in the provided CD.

1. Data analyse
   1.1 Data analyse-exp1
   1.2 Data analyse-exp1-reference
   1.3 Data analyse-exp2
   1.4 Data analyse-exp2-reference
   1.5 Data analyse-exp3
   1.6 Data analyse-exp3-reference
   1.7 Figures for chapter 5

   File location: Appendix\1.Data analyse

2. Simulation Version One Raw Data
   2.1 Acknowledgement
   2.2 Player 1
   2.3 Player 2
   2.4 Player 3
   2.5 Player 4
   2.6 Player 5
   2.7 SCV final data
   2.8 Senario_1&2_template

   File location: Appendix\2.Simulation Version One Raw Data

3. Simulation Version Two Raw Data
   2.1 Acknowledgement
   2.2 Real demand information
   2.3 Experiment 1
   2.4 Experiment 2
   2.5 Experiment 3

   File location: Appendix\3.Simulation Version Two Raw Data